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Automation and Robotics for the Space Station:

Phase B Considerations

An OTA Staff Paper

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CONGRESS OF THE UNITED STATES
Office of Technology Assessment
Washington, D.C. 20510

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AUTOMATION AND ROBOTICS FOR THE SPACE STATION:

PHASE B CONSIDERATIONS

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NOTE: Program Plan for the Astronaut's Apprentice, a paper prepared by Dr. Rodger Cliff of the Defense Advanced Research Projects Agency (DARPA), is available from OTA, Program on Science, Transportation and Innovation. It describes one possibility for introducing advanced A&R technology into the space station.

CHAPTER 1

OVERVIEW AND CONCLUSIONS

Automation and robotics (A&R) have been the subjects of important studies conducted by the National Aeronautics and Space Administration (NASA), its contractors, and advisors during the concept development and definition phases for a publicly-funded U.S. space station. The motivation to conduct these studies has come largely from intense national and Congressional interest in U.S. industrial competitiveness, and specifically an interest in the extent to which the space station can become the showcase of advanced technology for industrial automation, including primarily advanced computing (particularly artificial intelligence, AI) and robotics. Participants in these studies have included NASA researchers and project personnel, aerospace contractors, research institutions, and many expert consultants. Voluminous, in-depth, thought-provoking reports have been published as the official record of these studies.

The statutory authority for these studies was provided by Public Law 98-371 of the 98th Congress, dated July 18, 1984. The relevant passage of PL 98-371 is the following: "Provided further, that the [NASA] Administrator shall establish an Advanced Technology Advisory Committee [ATAC] in conjunction with NASA's Space Station program and that the Committee shall prepare a report by April 1, 1985, identifying specific space station systems which advance automation and robotics technologies, not in use in existing spacecraft, and that the development of such systems shall be estimated to cost no less than 10 percentum of the total space station costs."

The Office of Technology Assessment (OTA) first became involved in these issues in early 1984. At the request of the Senate Committee on Appropriations, Subcommittee on HUD - Independent Agencies, OTA conducted an exploratory workshop in March of that year. On the basis of the workshop, OTA concluded that both advanced A&R and future space operations would benefit from a close coupling to the space station program. Thus, the space station program could be an appropriate vehicle to advance the state of the art in A&R, provided that objectives are carefully chosen and early expectations are not unreasonably high. The findings of the 1984 workshop were presented in OTA testimony before the requesting Subcommittee on March 29, 1984.

Subsequently, the Senate Committee on Appropriations recommended the following NASA responses in Report 98-506 of the 98th Congress, 2nd Session (Calendar No. 967) to the challenges of advanced automation and robotics:

> ... the Senate bill requires ... a NASA automation report. This report and the ongoing NASA-sponsored automation study are expected to be completed no later than April 1, 1985.
>
> "The Committee also expects the contractors (i.e., the Space Station Contractors) to devote a significant portion of their effort pursuing the study of automation and robotics technologies identified in the [ATAC] report with the objective of advancing the state of the art in these technologies and increasing their terrestrial application.
>
> "The Committee acknowledges the need to pursue a manned space station; however, the Committee believes that NASA needs to pursue the areas of automation and robotics more vigorously. Consequently, the bill language is intended to assure that such advanced technologies are indeed made an integral part of the planning and development for a manned space station." [Emphasis added.]

This OTA Staff Paper is the product of a study undertaken at the request of the Senate Committee on Commerce, Science, and Transportation, and its Subcommittee on Science, Technology, and Space. The Committee requested that OTA "look at how automation and robotics initiatives can be incorporated into the space station definition phase." Given the language quoted above from PL 98-371 and from Report 98-506, OTA understands the intent of the Committee's request to be a report on the progress being made toward incorporating a significant level of advanced A&R into space station program planning. In the course of this study, OTA convened two workshops, one to consider potential international A&R initiatives, and the other to examine the prospects for inclusion of significant A&R initiatives in NASA's Phase B (system definition) planning for the space station program. OTA also reviewed NASA Phase B planning and talked with NASA managers.

Chapter 2 of the report briefly reviews the major findings of each of the studies undertaken in response to Public Law 98-371, with particular emphasis on identifying outstanding issues and questions that remain unanswered. An assessment of the "realism" of the proposed initiatives is also included. Chapter 3 assesses the extent to which A&R initiatives proposed in the prior studies are being factored into space station Phase B studies. Chapter 4 briefly reviews the extent of the national resource base in A&R that can be tapped for space applications, and Chapter 5 identifies U.S. industries that could benefit significantly from A&R technology developed for the Space Station.

CONCLUSIONS

FINDINGS

In preparing this Staff Paper, OTA consulted with experts in the areas of automation and robotics, space station design and planning, and NASA operations. A review of existing studies was conducted, and previous work performed at OTA in a number of related areas was analyzed. OTA has reached a number of conclusions based upon this work. The principal finding is clear. If the projected level of NASA funding for automation and robotics holds, and the current plans for the space station determine the eventual IOC configuration, two things are inevitable. No significant advances in the state of the art of automation and robotics are likely to result from NASA activities, and the eventual evolution of the space station beyond IOC will be hampered. If the Congress wishes to alter this situation, some specific action will be required. The components of this conclusion are listed below.

- **NASA is not planning to use space station program money for A&R research except in a few selected areas where it cannot be avoided. The program will fund applied development in A&R, from existing laboratory demonstration devices to operational space hardware, but only as needed by the IOC station.* Under these circumstances, Space Station A&R is unlikely to have significant impact on terrestrial automation and robotics capabilities.**

- **The only A&R research NASA plans to undertake lies in the OAST Program.** OAST's funding levels for A&R (which are not part of the $8 billion) are $8 million (1985), $10 million (1986), and (as proposed) at least $12 million (1987) -- far less than the $100-190 million per year that the ARP report recommends for advancing the state of the art. **As currently funded and managed, OAST's A&R research is not likely to have a strong impact on space station capabilities or on the state of the art in terrestrial automation.**

- **Unless NASA funds A&R research at levels substantially greater than the current and projected levels of OAST funding, the generic technology base in**

---

* NASA interprets PL 98-371 as meaning that Congress will appropriate funds, over and above those required for space station development, to carry out an A&R research program. NASA is, therefore, very reluctant to use space station program money for A&R research (in contrast to development) unless there is assurance from Congress that use of funds from this source will not diminish funds available for direct application to space station development.

advanced A&R is likely to hamper space station capability beyond IOC. For example, without a vigorous NASA A&R program, especially in the area of systems autonomy, the space station may not be optimally effective and productive for scientific users.

- **NASA's investment in generic technology base advancement and application engineering is believed likely to be recouped in eventual savings in the station's operational costs, which loom as a major funding problem for the space station.**

- **At the present time, there is little need for further concept studies in A&R.** The studies done for NASA have been useful in describing the potential of A&R for the space station program, but the marginal return on additional studies is insufficient to justify further delay in initiating an aggressive A&R research program. **The directions that A&R research could take to increase the likelihood that the NASA space station will become an ever more valuable national asset, as well as the probable benefits that an active NASA A&R research program could have on terrestrial A&R, are now well understood.**

- **If the Congress wishes to see the NASA space station program become a focal point for advancing the state of the art in automation and robotics, it will have to issue NASA more explicit guidance to that effect.** NASA management has taken the understandable position that the space station program has as its primary goal the provision of an operational IOC station. By its categorization of A&R technologies as (1) necessary to the space station, (2) desirable for the space station, or (3) unnecessary for the space station, even if highly desirable for terrestrial industry, NASA management has adopted the position that the advancement of terrestrial A&R technologies is not a central justification for the space station program.

CONGRESSIONAL OPTIONS

The following policy options are intended to illustrate the range of possibilities open to Congressional action if the Congress wishes to increase the level of NASA commitment to A&R research. They are not meant to exhaust all possibilities.

> In order to advance the state of the art in A&R and to approximate the support level recommended by the Automation and Robotics Panel, stipulate that 10 percent of space station funds within the $8 billion envelope be spent on A&R research (not development). **This option could result in major A&R advances for the U.S. economy at the expense of some disruption and delay of the IOC phase of the space station program. It would require trading off some currently envisioned level of space station capabilities in one or more other areas, e.g., giving up 25 of the currently planned 75 kilowatts of power, in favor of an advance in currently envisioned A&R capabilities. Funding at this level would push the state of the art in space A&R very rapidly, so that the IOC station, when completed, would have substantially greater A&R capabilities than now planned.**
>
> **Stipulate that the NASA OAST Program will support A&R research at a level of 10 percent of space station funding, while leaving the space station program intact at the $8-billion level.** This option would entail OAST's undertaking a new role. The sheer size of the 10 percent funding would be far greater than any project OAST has undertaken and would tend to dominate

smaller, but important, OAST activities. In addition, the Congressional intent that the A&R research be focused on the space station would require OAST to adopt a much closer connection with an operations program.

Establish an advanced A&R capability outside OAST, either on the program level, independent of the space station program, or as a separate line item within the space station program, and appropriate additional funds outside the $8 billion IOC envelope to support it.

IMPLEMENTATION

The following options with respect to implementation could be considered in support of any of the options above, as well as at this time. They would serve to clarify and strengthen the commitment to A&R research. Initiatives might come from the Congress or NASA.

- Establish explicit criteria for what will count as advanced A&R and for monitoring research accomplishments.

- Strengthen NASA's in-house technical expertise in manufacturing A&R. It is unlikely that this rapidly changing technology can be incorporated into the space station program effectively unless NASA managers have first-hand experience with advanced computer-integrated automation technology. Exactly how NASA's expertise in this area should be strengthened is a matter for further study.

- Adopt NASA standards for databases, communications protocols, and interfaces that are based on current industrial and international standards and/or standards research.

- Designate a NASA Center as the focal point for NASA research and development in A&R. Most major organizations committed to A&R have established such a center/activity within their overall structure. A lead Center could help make NASA a knowledgeable and informed buyer and user; it may also be the only way NASA can assemble a critical mass of researchers and technologists.

- Create an independent, at least partially non-NASA, panel to identify critical problems in the space station program where potential A&R solutions could be appropriate. The panel might also serve to bring new A&R developments to NASA.

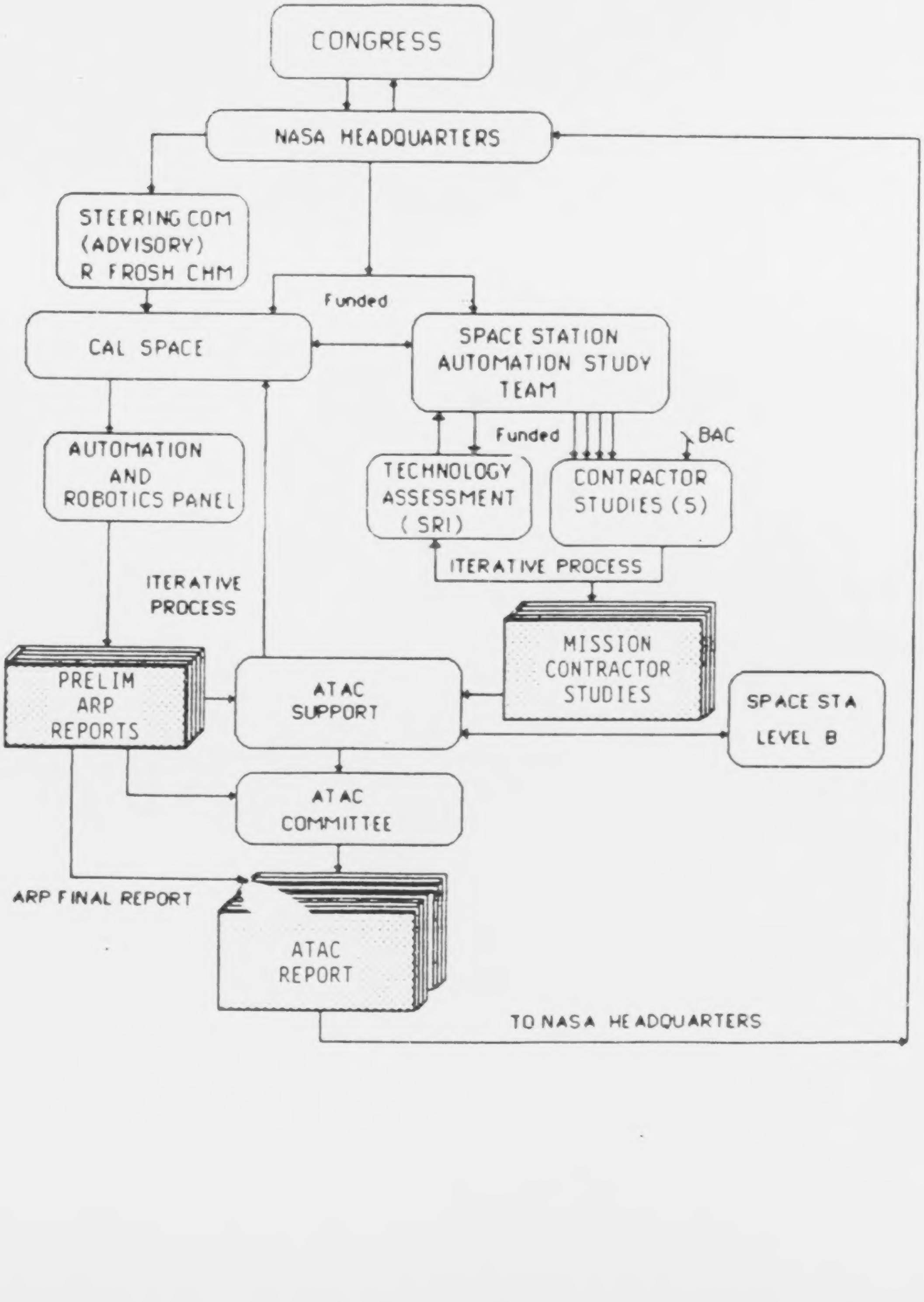
- Increase the pure research percentage of OAST's A&R funding, perhaps up to as much as 60%. (Of the remaining 40%, two thirds could be allocated to ground-based demonstrations, and one third to flight experiments; because the latter are primarily of interest to and for application by users, they could be funded principally by the appropriate user office.) The OAST research activity could well be focused on high-risk technology applicable to both telerobotics and systems autonomy.

CHAPTER 2

REVIEW OF SPACE STATION AUTOMATION & ROBOTICS STUDIES

Five aerospace contractors studied particular topics related to space station automation and robotics (A&R). They developed specific recommendations regarding the mission needs and technical feasibility of deploying sophisticated levels of A&R into space station systems as they evolve from the Initial Operating Capability (IOC) toward the mature station. SRI International used the results of these studies and its expertise in the underlying technologies to assess the readiness of automation and robotics to meet NASA's space station aspirations and to identify the major technology-related issues which must be addressed in order to realize the A&R potential of the NASA space station. The California Space Institute (CalSpace) organized an independent panel of experts (the Automation and Robotics Panel, or ARP) to conduct a separate study, intended to provide an independent view of the A&R possibilities and to recommend an approach to meeting the intent of Congress as stated in Public Law 98-371. These seven studies were provided to NASA's Advanced Technology Advisory Committee (ATAC), which had the responsibility to translate the recommendations into agency policy. The relationships of these seven studies are illustrated in Figure 2-1. An additional study was sponsored by NASA, independent of the space station studies, but sufficiently relevant to warrant summary in this report. This study, "The Human Role in Space" (THURIS), was conducted by McDonnell Douglas; it explores ways of optimizing the mix of automated systems and humans in space.

Figure 2-1: Relationships of the 1984-1985 Space A&R Studies



AEROSPACE CONTRACTOR REPORTS

The intention of the studies assigned to aerospace contractors was to address, without regard to cost,* what automation and robotics (A&R) applications might be included in the evolutionary station:

- to help support development of policy recommendations;
- to serve as examples of a way to conduct conceptual design studies in A&R; and
- to identify relevant technological research and development (R&D) issues, and the "scars" (hardware features supporting evolutionary growth) and "hooks" (software features supporting same) that should be included in the Initial Operating Capability (IOC) space station.

Each study examined technology in a specific functional area, all studies but Boeing's assigned by NASA.

THE OPERATOR-SYSTEMS INTERFACE (BOEING)

Boeing explored the concept of how an operator interfaces effectively with an extra-vehicular robot to perform a variety of servicing and repair functions for the space station. Figure 2-2 illustrates Boeing's concept of such a robot. The Boeing study employed sample scenarios in order to identify functional requirements and underlying technologies of the proposed operator interface. A technology assessment is provided based on an extensive study done for the French and Japanese governments by Systems Services Transnational (SST) in 1981 and updated in 1983 (the "Transnational Assessment

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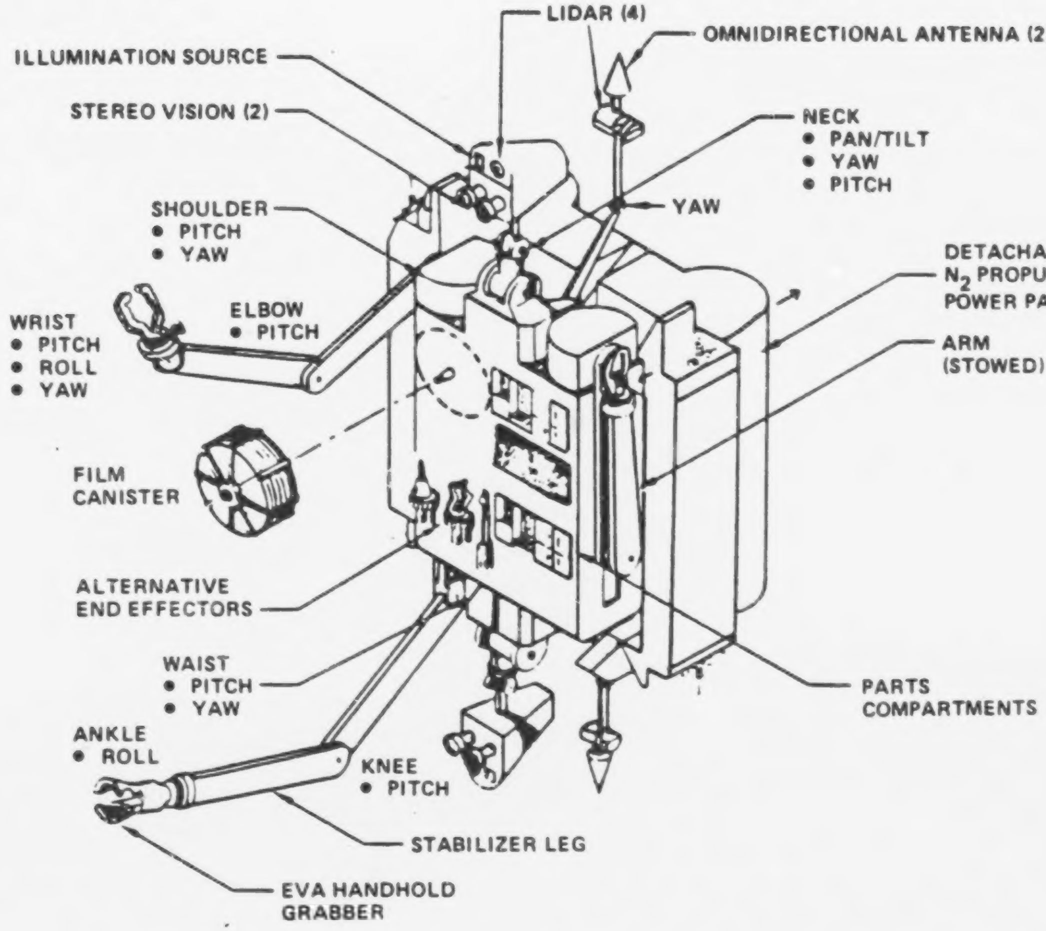
* The fact that cost is an absolutely central factor in the considered development of space -- a development which advanced A&R may help to make possible -- casts a certain doubt on the pragmatic value of these studies.

Figure 2-2 Boeing Extra-Vehicular Robot Concept



of Autonomous Robotic Generational and Evolutionary Technology," or TAARGET study)

Boeing's fundamental premise is that there are at least two paths leading to the successful utilization of robotics in space. The traditional path would maintain man-in-the-loop control via teleoperation and gradually increase the level of autonomy; an alternate path would begin with relatively simple autonomous robotic systems and increase the complexity of these systems as technology matures. Both approaches would support feasible IOC applications, the selection of the appropriate path being a function of the characteristics of task to be performed -- its complexity, frequency, requirement for human involvement, and the availability of crew time.

Because a 2010 space robot will be considerably more sophisticated than its IOC counterpart, Boeing, in order to surface operator-system interface requirements and the underlying technology needs, studied the concept of a semi-autonomous robot, with human supervisory control, performing a moderately complex maintenance task.

The operator-systems interface (OSI) Boeing proposed includes visual and aural stimuli. Projections for IOC include connected speech processing with a 5000 word vocabulary and 2-D image interpretation. Evolutionary space station technology for OSI emphasizes advances in information technologies such as monotonic and non-monotonic reasoning, analogical reasoning, heuristic search, knowledge acquisition, knowledge representation, sensor fusion, image understanding, stereo vision, and information fusion.

Two distinguishable technology development paths have been proposed, each leading to highly capable space-based robots. One approach infuses teleoperator technology with increasingly higher levels of supervisory control capability. As a result, the operator would be initially responsible for every movement of the remote device; subsequently, he would be able to relinquish progressively more control of the remote system, until eventually his primary activities would be high-level command and monitoring functions. The alternative is to begin with relatively simple "autonomous" robots and make them progressively more capable while retaining the fundamental concept of autonomy.* While NASA's Office of Aeronautics and Space Technology (OAST) has developed its research and development agenda around the former approach, Boeing believes that both approaches have viable applications. Emphasizing autonomous robots might better promote spinoffs enhancing ground-based industrial productivity, but at this point both approaches seem to be worth pursuing.**

A major distinguishing feature between the two approaches resides in the operator-system interface. A teleoperated system is envisioned as including a richer sensory environment, including force/torque commanding by and feedback to the operator. It also enables a richer teaching repertoire, including a master's style of showing an apprentice how to learn a new skill. The overall means by which one will program a remote manipulative device circa IOC*** is a fundamental issue. Whereas Boeing suggests that voice commands, joysticks, and color graphics are the key interface media, and automated planning the core technology, OAST's approach admits anthropomorphic, "Here, let me show you," teaching.* Consideration of time delay in the command communications channel clarifies the debate. If there is essentially no time delay, then the OAST system appears to be a simple teleoperator. As the time delay grows arbitrarily long, then the operator's functions necessarily become "programming" via physical movement of his limbs, for direct control with delayed feedback results in instabilities.

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* There is also a sense in which the distinction between these approaches is more philosophical than real; both begin with an operator in the control loop.

** Many technologists believe that the human-machine interface is a critical area for development as it applies to space; others believe human-machine interface studies could become a "sink" for large amounts of A&R funds.

*** "IOC," as used here, means the time frame within which the Initial Operating Capability is expected to be achieved. Currently, this is estimated to be approximately 1994.

* One fundamental limitation to the Boeing approach is that the overall system capability will be limited if difficult cognitive burdens are not initially assigned to humans. The telerobot being developed at the Jet Propulsion Laboratory by NASA's Office of Aeronautics and Space Technology does indeed have a teleoperation capability, but the emphasis is upon low-level autonomy of the sort envisioned by Boeing. Human beings will remain responsible for the overall effectiveness of the system in either case.

Common to both approaches is the need to program a robot. The OAST approach employs on-line programming, where real objects are used; the alternative approach, off-line programming, uses simulated objects. In either case, programming code is generated by a human programmer, not automatically. Manual programming is tedious and prone to human errors, whether it is generated on line or off line, because the bulk of the program consists of logic and control statements. The only way to overcome this problem is to develop a software system for automatic planning and programming. Technology readiness for space application is a concern, since historical progress on automatic programming has fallen short of expectations.

The choice of approach used to develop remote manipulation technology for the NASA space station is a pervasive issue, affecting not only the capability of space-based robotics, but also the U.S. technology base in advanced robotics and related disciplines. Remote manipulation is important for all tasks that cannot be executed manually or by a fully automated robotic system.

A secondary issue relating to the Boeing study is the extent to which NASA R&D activities can and should contribute to speech understanding, speech synthesis, and natural language understanding. This issue involves the scope of current relevant national programs and the marginal return on further R&D investment. DARPA's Strategic Computing Program is already investing heavily in the basic technologies, but NASA may have to fund applications efforts in order to obtain practical systems for the publicly funded U.S. space station.

Boeing's projections are based on a technology assessment that includes an extensive literature search, as well as a Delphi process involving recognized experts. The process suggests that the proposed technology targets are realistic.

The argument that leads to the conclusion that the evolutionary path should start with autonomous robots is derived from the Delphi question, "As defined, can autonomous machine (robotic) technology evolve naturally (i.e., without major technical innovations/changes) from current teleoperated robotic technology?" The experts polled answered with a clear "No!" The key phrase in the question, however, is, "without major technical innovations/ changes."* OTA believes, however, that both approaches will require major advances.** Thus, the Boeing conclusion in favor of beginning with a relatively simple autonomous system and directing its evolution toward greater capability (while retaining autonomy at every stage) may have been too strongly driven by the wording of the Delphi question. Nevertheless, the response to the Delphi question does reveal that teleoperation, by itself, will not lead to the development of all the technologies (e.g., analogical reasoning and non-monotonic reasoning) needed for advanced robotics. That is, there is substantial development work to be done in robotics that is not motivated by teleoperation requirements.

The OSI technologies addressed in the Boeing study are highly relevant to space station operations in general, regardless of the specific approach chosen to meet space robotic needs. Each of the Phase B contractors needs to address the development of effective interfaces between space station systems and their operators, both in space and on the ground. To make human-machine interactions more effective, speech and natural language interfaces will have to be a significant part of the interface, as well as effective visual displays that fuse design data (e.g., from Computer-Aided Design, CAD, data bases) with observed data.

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* The phrase "from current teleoperated robotic technology" is also significant. Unless the respondents were familiar with the state of the art in a number of diverse areas, including the space, undersea, and nuclear fields, they might have judged the overall capabilities of current teleoperators to be more limited than they really are.

** The OAST and the Boeing approach for achieving autonomous robots are based on different constraints: OAST requires the application of robots while R&D is performed, while Boeing is concerned primarily with the goal of robot autonomy. In either case, the real issues are technological breakthroughs that will enable machines to perceive and act appropriately under unpredictable conditions. It is interesting to note that Boeing focused on facilitating man-machine interaction, a major issue in teleoperation.

IN-SPACE MANUFACTURING (GENERAL ELECTRIC)

In order to study generic aspects of space manufacturing, General Electric took as an example task the automating of in-space manufacturing of gallium arsenide Very Large Scale Integrated (VLSI) devices. An in-depth design study was conducted that explored: (1) electroepitaxial crystal growth and wafer manufacturing, and (2) microelectronics chip processing. Figure 2-3 illustrates GE's concept for an automated gallium arsenide's crystal production and wafer manufacturing facility. Figure 2-4 illustrates the concept for the automated microelectronics chip processing facility. The ultimate objective is to manufacture high-quality, high-yield devices automatically in space, directly from raw materials. According to GE, the crystal production and wafer manufacturing facility could be constructed by IOC, five years prior to the microelectronics chip processing facility. A fully integrated facility is projected to be feasible circa 2000. The facility would be human-tended but normally run by teleoperated and robotic devices. Major advances in artificial intelligence, particularly as applied to robot control, fault diagnosis, and multi-agent process control are deemed necessary.

The most important aspect of the GE study is its identification of research topics in manufacturing and repair devices that will be critical to future space industrialization and unique to NASA's trailblazing mission. The study also has relevance to ground-based manufacturing. The technology development required for such a space-based manufacturing facility could have broad applicability to manufacturing processes in various industries, and can legitimately be considered pioneering. No comparable facility exists either in space or on the ground. Its value could lie both in using space resources and the space environment to advantage in processes that produce economically competitive products, and in performing a pathfinder role in advanced automation for the factory of the future.

Figure 2-3 Gallium Arsenide Crystal Production and Wafer Manufacturing

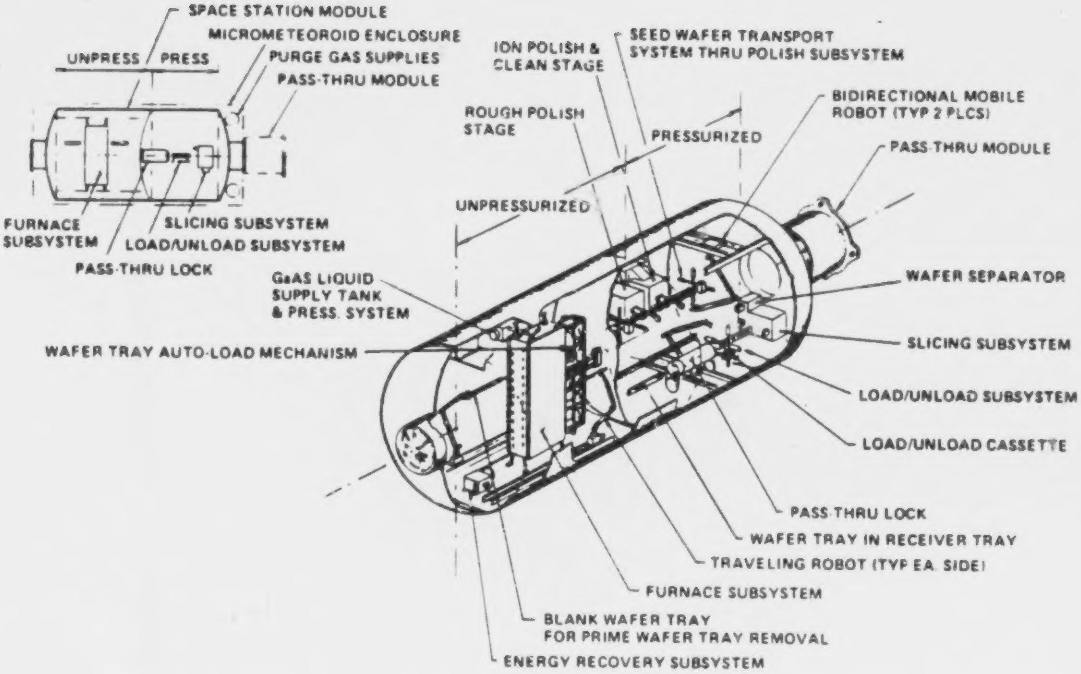
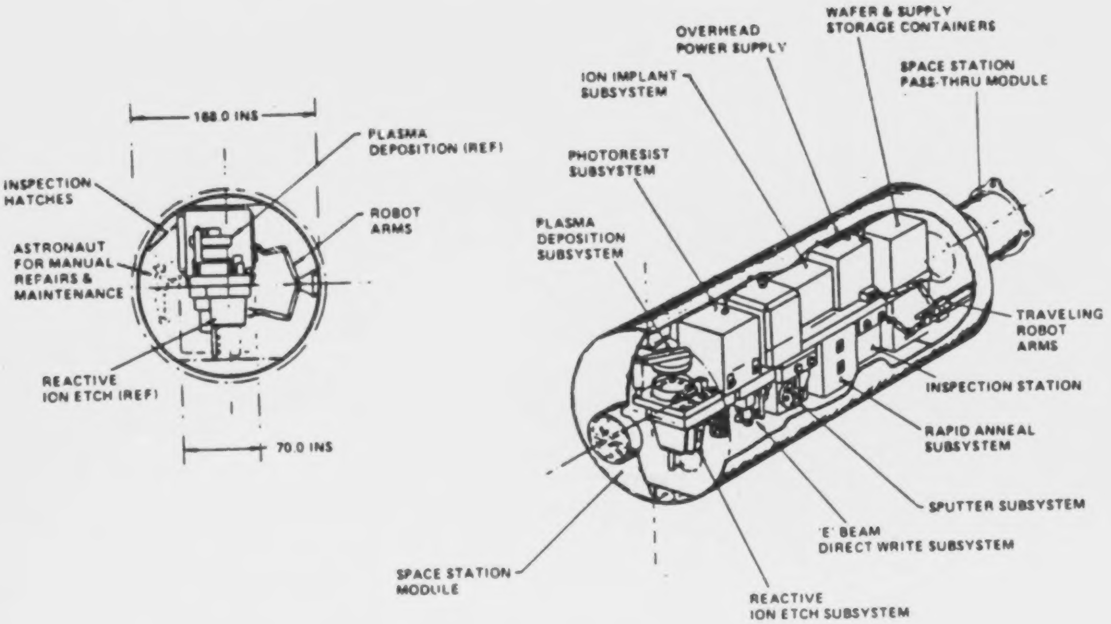


Figure 2-4 Gallium Arsenide Microelectronics Chip Processing Facility



The manufacture of high-quality, high-yield gallium arsenide devices could benefit from the microgravity environment of space, especially if steps are taken to make the immediate environment ultra-clean. Unfortunately, the manufacturing process is a power-intensive application, requiring about 1/3 of the available electrical power expected to be available from the NASA space station.*

GE proposes an evolutionary development and implementation of automated in-space manufacturing capability. An early dependence on manual operation and teleoperation is envisioned, with a subsequent use of deterministic, algorithmic controllers for well-understood processes. AI-based solutions are expected to emerge thereafter, culminating in the extensive use of intelligent robots and expert systems *circa* 2010.

General Electric identified a series of technology-related issues crucial to the success of an in-space manufacturing plant. These include:

- long-life, continuously working mechanisms;
- long-life dry lubricants;
- self diagnostics;
- modular designs and simple interfaces to facilitate maintenance and repair by robot;
- handling of fragile wafers in microgravity;
- dual-mode manipulators for teleoperated and robotic operation; and
- automated techniques for performing quality assurance (currently achieved by human inspection).

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* A central problem for the considered development of space is to learn how to drive down the cost of electricity in space in order to take advantage of microgravity in A&R-assisted space processing.

GE proposed that these issues be addressed through a 7-year technology development program totaling $26M.

Several important questions relevant to in-space manufacturing were not addressed in GE's study:

- Can gallium arsenide devices be cost-effectively manufactured in space?
- Will the market for these devices be sufficient to justify the technology investment in building the capability? (It should be noted that the GE study did not attempt to assess commercial viability prior to addressing A&R issues. As desirable as such a study might be, there were insufficient resources to support it.)
- Will other manufacturing industries benefit sufficiently to justify the investment, even if gallium arsenide devices do not provide sufficient payoff?
- How can in-space manufacturing technology support ground-based manufacturing processes and industrial competitiveness?
- How can waste products be effectively disposed of without risking pollution of the space station environment?
- Can waste disposal adversely affect any other operations of the space station?

The proposed technology development plans depend on major advances in AI, and particularly in highly complex, cooperating expert systems. These are currently well beyond the state of the art. Success of this project depends on technology breakthroughs that may be some 5-10 years in the future -- an uncertainty that introduces some technological risk. However, with all of DARPA's Strategic Computing Applications

Programs involving significant numbers of cooperating expert systems, it is likely that the technology will be in hand when needed by the space station. This same technology promises to result in very high payoff in applicability to many space station control problems, as well as in transferability to extensive ground-based applications. However, the technology and study agenda suggested by GE is almost certainly insufficient to meet the needs of its proposed manufacturing project.

The GE study addresses the processing steps required to manufacture the gallium arsenide devices in space. The major open questions lie not in the process domain, but in the interprocess domain. For example:

- How is material to be moved from process to process?
- How are system components involving multiple processes and their interactions to be scheduled, operated, diagnosed, and repaired?
- How can the safety of the flight crew be ensured while they are in the manufacturing module?

GE performed a comprehensive survey of existing manufacturing processes and the state of technology supporting them. The proposed schedule for deployment of manufacturing technology in space was based on extensive knowledge and experience in both manufacturing and space-based operations. The required advances in AI may have been underestimated, and almost certainly the investment required to achieve these advances has been underestimated. Similarly, GE may have been overly optimistic about the state of the art in teleoperation. Thus, even though a great deal of progress could be made in fifteen years, GE's manufacturing program would require an aggressive R&D program over that entire period.

The General Electric study is highly relevant to Phase B studies and is worth careful consideration by the Phase B contractors. In general, GE has outlined the parameters for repair and basic manufacturing that the design for any future manufacturing facility will have to take account of. Before any such facility is actually built, of course, these parameters will have to be more carefully studied. Of particular importance for the near term, however, is provision of appropriate hooks and scars on the space station to support in-space manufacturing facilities. Given its long-term promise, Phase B contractors might well be required to design for sufficient space station utilities (e.g., power, thermal control, and data management) to support resource-intensive manufacturing.

HUGHES STUDY

Subsystem Control and Ground Support (Hughes)

The Hughes study examined the feasibility of autonomous operation of space station subsystems. It focused primarily on the communications subsystem, but also looked at electrical power and thermal control. The fundamental operations concept consists of an automated system for monitoring and control that detects, isolates, and recovers from failures. Direct user control of space station payloads without interaction with ground controllers is also envisioned. Substantial emphasis was placed on using existing and evolving standards wherever appropriate in order to place the space station within a larger international infrastructure of resources accessible and operational via standard communications resources.

The Hughes study makes the following seven recommendations:

- Design space station communications as an end-to-end system between user and equipment;
- Use commercial digital telephony standards;
- Process user service requests automatically in real-time and

provide demand assignment of selected services;

- Do short term planning and scheduling automatically on-board the station;
- Implement an automated command screening system;
- Use speech recognition and synthesis in the human interface for command and control; and
- Design the data management system and other space station subsystems to accommodate future, fully automated fault detection, isolation, and recovery.

Hughes concludes that major steps towards space station autonomy can be made using state-of-the-art technology wisely. Even without giant strides in these technologies, powerful interactive aids can be made accessible to the flight crew to minimize their dependence on the ground. The principal technology drivers for the future were seen to be planning and scheduling; fault detection, diagnosis, and recovery; and real-time knowledge-based systems.

The Hughes study regards problems in the electrical power, communications, and thermal control areas to be engineering issues rather than technology issues. The current state-of-the-art is viewed as sufficient in those disciplines. The study identified the major issues as lying in the base automation disciplines.

The study clearly identifies adoption of international standards for system design (e.g., communications protocols and digital telephony standards) as a key issue which affects the overall accessibility of the space station.

Providing ground-based users direct access to space-borne payloads would represent a major change in NASA's operating mode. Operating in this new mode would require essentially error-free user authentication, as well as rigorous checking of system constraints and command consistency. The system will also need to be able to detect interacting sequences of events involving multiple payloads: even though each sequence by itself is safe, when several are combined, undesirable effects may be introduced.

Hughes does not project technology requirements or recommend a technology development program. The study does, however, identify the key topics to be:

- planning and scheduling;
- fault detection, diagnosis, and recovery; and
- real-time knowledge-based systems.

Several important questions arise from the Hughes study. If these technologies are pushed hard, how might they affect IOC? How might they influence the space station 5-10 years after IOC? How should the space station be designed to accommodate expected advances in these areas? Are current engineering standards sufficient?

Hughes has laid out a realistic approach to providing a space-based resource that maximizes utility to the user community. The technical complexity of automating electrical power and thermal control with state-of-the-art technology may have been underestimated, however. At least two aerospace companies (TRW and Martin Marietta) have encountered only modest success in recent efforts to automate the control of space-borne electrical power systems.

The use of international communication protocols and standards is an interesting proposal that deserves further study. Although potentially imposing higher overhead and short-term incompatibility with existing NASA communications systems, it may offer long-term economic advantage and greater accessibility.

The Hughes study is highly relevant to Phase B space station studies. Its principal emphasis is on what can be accomplished with existing knowledge and state-of-the-art technology. This is precisely the Phase B problem. If the Hughes study is to be faulted on any ground, it is perhaps on that of having placed too great an emphasis on IOC.

MARTIN MARIETTA STUDY

Autonomous Systems and Assembly

Martin Marietta examined application mission requirements that drive space automation technology, concluding that communications, material sciences and processing, and satellite services are categories of "obvious growth." Martin then explored two aspects of space automation: subsystem autonomy and in-space assembly and construction.

Martin listed the potential advantages of in-space manufacturing as:

- zero-G (weightlessness);
- vacuum (low drag, acoustic isolation, off-gassing, no thermal convection, etc.);
- unlimited reservoir for dumping (waste heat, hazardous materials, etc.);* and
- solar energy.

Martin concluded that the staged achievement of system autonomy, i.e., the evolution of systems previously functioning by means of ground-based control or astronaut attendance into on-board automated systems, is an important goal for the NASA Space Station Program. Around 1990, experimental knowledge-based systems are to be constructed on large machines with sophisticated development environments. By 1992, these experimental systems will evolve to smaller target machines on the ground which resemble space-borne symbolic processors appropriate for IOC. The next step is to qualify the software for space use and install it on on-board computers.* Principal technology needs were identified as deep reasoning, learning, prediction, natural language, and planning.

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* To use the space environment, especially near-Earth space, for dumping seems to most experts to be highly undesirable.

* Space qualification of any knowledge-based system using symbolic processors is no

With respect to assembly and construction, Martin concluded that the evolutionary path begins with extra-vehicular activity (EVA, or "spacewalking"), then adds telepresence capabilities. As experience develops with space telepresence and as technology matures, supervisory control is introduced. Ultimately, "tele-automation" becomes the mode of operation. The suggested research emphases include predictive displays; proximity, force, and touch sensing; sensor fusion; dual arm coordination; knowledge-based systems; and strategic & tactical planners.

The Martin study focused largely on engineering concepts and issues which would facilitate achievement of higher levels of advanced automation (including AI) in the space station. For instance, it set out an evolutionary subsystem control scenario which projects the development of current concepts and modes of operation of remote systems into on-board intelligent autonomous systems. In assembly and construction, the emphasis tended to be on design guidelines to facilitate automated assembly for station add-ons, large satellites, remote unmanned platforms, and manufacturing facilities. Tooling, fixturing, and connecting, for example, were examined, with the importance of commonality among structural elements and construction support equipment clearly identified.

Although Martin's recommendations include a ranked list of research and technology development areas, critical issues and suggested approaches leading to their solution were not crystallized; these areas were the responsibility of SRI and the ARP.

Martin's concepts of technology evolution in remote manipulation go from EVA,

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simple matter. Indeed, as NASA currently flight-qualifies software, symbolic processing programs, because of the non-deterministic nature of their algorithms, will never be allowed in the space station. Unless the space station's expert systems are to be written in Fortran, Ada, or some other (suboptimal) language, the whole question of the requirement and nature of software qualification needs to be addressed.

through telepresence, teleoperation, and supervisory control, to intelligent robotics. The relationship between telepresence and teleoperation remains an article of minor debate. Is, for example, telepresence a more sophisticated form of teleoperation in which a very rich sensory environment is provided, or is it a more primitive form of teleoperation that requires more direct control by the operator (with little or no dependence on computers and/or processors)? Martin suggests the latter.* Are the advantages cited for in-space manufacturing real, or do they merely conceal another problem? For example, can we really expect space to provide an unlimited dumping site for refuse?

Martin questions whether Ada is sufficiently mature for use as the primary programming language for the space station. The suggestion is that a language like "C" may be a safer choice. This issue is actually bigger than Ada vs. "C".** It includes the choice of language standards for A&R, as well, in which researchers prefer LISP and Prolog, languages that are vastly different from Ada. The broader issue is establishment of the overall software environment for the space station.***

Martin identifies the development of fixturing and tooling for space construction as yielding positive benefits for U.S. industry. Construction equipment can also be used for maintenance. Indeed, intelligent (flexible) automation in facility and equipment maintenance is likely to be of increasing importance -- not least because of its potential for cost containment -- in factories of the future. Space experience in this area could be useful in the development of intelligent robots for ground-based maintenance applications in hostile environments (e.g., nuclear fuel processing facilities, hazardous chemical plants, biological processing facilities, steel mills, mines and other high-temperature environments). Nevertheless, it is not entirely clear, however, how this benefit would accrue. For example, who would have the responsibility to disseminate transferable technology to non-aerospace industries?

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* It should be noted that Martin's terminology is out of step with the usage of the majority of the A&R community. The task Martin refers to as "telepresence" is more correctly termed "remote inspection," for it implies no capability physically to interact with the worksite environment. True "telepresence" in common usage is a level of capabilities, in terms of sensory feedback and command dexterity, beyond that of a common teleoperator. By definition it must include the capability for the operator to interact in a near-normal manner with the worksite.

** Martin did not recommend "C," but only used it as an illustration to establish a foil for Ada.

*** In order to increase its effectiveness and decrease its cost, an expert system, for example, should be developed in parallel with the system for which it is to be the expert (the object system). If the latter is developed first and its design team is dispersed before the expert system is developed, valuable design information and explanation will inevitably be lost. This problem will be exacerbated if the programming language of the object system is different from that of its controlling expert system.

While Martin recommends priorities for NASA research, these are, in accordance with NASA guidance, not presented in a national context. In that context, questions such as the following may be of particular interest to the Congress: How can the proposed NASA activities contribute to a national program? How can aerospace advances be integrated with commercial and defense advances to yield heretofore unavailable industrial capabilities?

Martin's results seem to be consistent with the prevailing wisdom regarding the potentially achievable pace of automation in space. A reasonably well-paced engineering-style program is outlined, which takes advantage of much of the existing aerospace automation technology base.

This study is highly relevant to Phase B studies, largely because of its pragmatic, engineering approach and style of presentation. It addresses critical aspects of the space station. Its results are of clear relevance to the Phase B contractors.

TRW STUDY

Satellite Servicing

TRW's study had two objectives: (1) to determine the current and potential capabilities of telepresence, robotics, and artificial intelligence, and their role in supporting on-orbit servicing of satellites as well as space station components, and (2) to define a generic servicing facility for the IOC space station that incorporates automation technologies for supporting or relieving the crew in servicing tasks. Four spacecraft servicing scenarios were considered:

- Gamma Ray Observatory (GRO),
- Materials Processing Facility (MPF),
- Space Station Attached Payload, and
- geostationary (GEO) satellites.

Figure 2-5 illustrates one of these scenarios. Typical time savings of 50% were reported as feasible using automated aids to servicing.* Servicing functions typically include refilling propellants, replacing modules, and performing automated inspection tests, diagnostics, & checkout.

Important satellite servicing technologies include:

- dexterous manipulation;
- spacecraft design-for-servicing guidelines;*
- space-qualified servicing robot;
- data systems;

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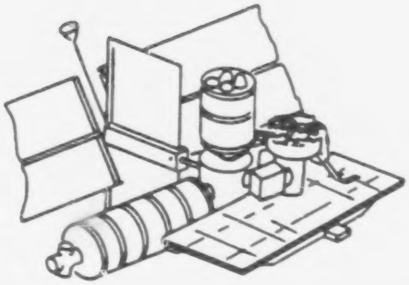
* This observation alone has little significance. The real issue is whether the savings are greater than the cost of achieving them. Explicit consideration of cost is essential.

* The phrase "design-for-servicing guidelines" disguises a thorny problem. On the one hand, several aerospace companies at the recent Rendezvous and Proximity Operations Workshop at NASA Johnson Space Center expressed the opinion that NASA (or a contractor) should produce design guidelines for satellite servicing, based on conceptual plans for a generic robotic servicer. They anticipated that satellites would then be universally produced to be compatible with the guidelines. On the other hand, spacecraft manufacturers uniformly argue that under no foreseeable circumstances would they commit the effort to design for a servicing system that does not exist. This fact had already been discovered in the course of the MIT ARAMIS contract with NASA and led to the conclusion that the best possible approach to satellite servicing would be to design the automated servicer to have the same capabilities as a human in EVA. This approach would have several beneficial results, including commonality, redundancy, and the current well-developed state of the art for EVA design.

Figure 2-5 Servicing of Space Station Attached Payload

1. SCENARIO HIGHLIGHTS
   - INSPECT PAYLOAD OR SUBSYSTEM TO BE SERVICED
   - CALL FOR AND RECEIVE REQUIRED PARTS OR SUPPLIES VIA ORBITER
   - TRANSFER SERVICING OBJECT TO AND FROM WORKSTATION
   - PERFORM REPAIR, REFURBISHMENT, AND MODULE REPLACEMENT
   - CHECK OUT AND RESTORE TO NORMAL OPERATION
2. AUTOMATION REQUIREMENTS
   - LOAD HANDLING AND TRANSFER
   - AUTOMATED TESTS, DIAGNOSTICS, AND CHECKOUT
   - MODULE REPLACEMENT BY TELEOPERATION
3. CREW ACTIVITY COUNT

   ESTIMATED ELAPSED TIME:
   2.9 HR WITH AUTOMATION
   6.5 HR WITHOUT AUTOMATION



- human to machine interfaces;
- in-space fluid transfer;
- robot vision;
- automated load handling & transfer;
- automated rendezvous & docking;
- Orbital Maneuvering Vehicle (OMV) and Orbit Transfer Vehicle (OTV) smart front ends;
- knowledge-based systems; and
- reusable OTV.

The first seven of these were considered to be top priority needs. TRW recommends a servicing approach that employs teleoperated servicing in the IOC time period and evolution toward robotic servicing *circa* 2000.

TRW's major conclusions were:

- Automation can improve productivity of satellite servicing, but accelerated technology development is required.
- The requirements of satellite servicing are quite different from those of other orbital activities.
- Telepresence is required to handle the diversity and unexpectedness of servicing situations.
- Compatibility of manipulators between teleoperation and robotics offers flexibility and adaptability.
- Scheduling servicing scenarios while line-of-sight communication exists avoids having to deal with time delay.
- GEO servicing will force the operating mode towards supervisory control; the operator will likely be on ground.
- Massive data system support is required for planning,

sequencing, execution, troubleshooting, failure analysis, and other emergency situations; AI is an important technology here.

- Terrestrial spin-off is likely to be primarily in flexible/adaptable automation, emphasizing economical production of small quantities.

TRW argues that "teleoperation requirements are more numerous than robotics requirements, at least in the early space station operating phase." This conclusion stems from the "one-of-a-kind" nature of most satellite servicing activities. This conclusion also raises the issue of the proper relative balance between teleoperation/telepresence, robotics, and AI research and development. Telepresence minimizes EVA, enables load handling and transfer, enables remote servicing, and more readily adapts to unforeseen conditions than more highly automated approaches. Robotics reduces overall crew involvement, potentially increases the precision available for parts handling, and can speed up the servicing schedule, but realizes its true economic edge in those situations where some repetition of operating sequences is encountered. Furthermore, subsequences can be automated so that the human operators need not be confronted with repetitive situations at the gross level. Artificial intelligence as an aid to human decision processes can be valuable. Crew time can be saved while levels of station autonomy are increased. Some evidence suggests that quality of decisions can also be improved.

In TRW's study attention was drawn to some advantages in scheduling remotely controlled, in-situ servicing tasks for time intervals of direct visibility, rather than using the complex, multiple-leg relay link via the Tracking and Data Relay Satellite System (TDRSS). These advantages accrue primarily because using TDRSS involves significant delays in the control loop. The current TDRSS design does not provide for single-relay communications paths between the space station and another satellite, but requires at least eight communications laps to and from geostationary orbit, via White Sands Ground Terminal and POCC. (TRW's approach does not specify reliance on pre-scheduled direct line-of-sight communication from the space station to the the satellite to be serviced.)

TRW's approach advocates the evolution from teleoperation to robotics, where the same manipulators can be employed in different control modes. This approach, shared by other study teams (notably SRI's), permits human operator involvement, as a back-up option, in performing servicing tasks by teleoperation whenever the task profile or complexity exceeds the capability of purely robotic manipulation.

TRW's cautious approach to integrating expert system capability into servicing operations, allowing enough time for this technology to mature, is also in direct agreement with the caution advocated by SRI.

The TRW study is highly relevant to Phase B planning. TRW addressed A&R issues and technology requirements directly concerned with enhancing crew productivity in servicing and with enabling important servicing missions. In-situ servicing is one of the objectives that may drive A&R technology development.

It is clear that a variety of opinions exists among the aerospace contractors regarding how best to advance toward highly capable space-based robots. TRW and Martin Marietta suggest a rather different evolution than does Boeing, for example.

SRI INTERNATIONAL STUDY

Technology Assessment

SRI International constructed a comprehensive report based on its analysis of the five aerospace contractor automation studies, summarized in previously in this report. SRI ranks automation applications for the space station and assesses technology needs with respect to them. A detailed R&D agenda, complete with recommended demonstrations to measure progress, is proposed. The proposed research addresses:

- design for automation;
- teleoperation and robotics;
- sensing;
- expert systems;
- automatic planning;
- space station information systems; and
- human interface.

SRI consolidates the aerospace contractor findings into the following conclusions:

- Teleoperation & Robotics: Evolve from telepresence to intelligent robots.
- Sensing: Complement DARPA Strategic Computing Program R&D, emphasizing visual and tactile sensors.
- Expert Systems: Focus on applications in dynamic domain, such as "reasoning about the effects of sequences of actions and tests that can change the state of the world over time." NASA's systems must also reason about concurrency of subsystem operations and interactions among subsystems.*
- Planning: Multi-agent planning is critical for the space station, and NASA support may be necessary to augment the work done by other agencies. Some spinoff may be available from DARPA's Battle Management and Pilot's Associate programs.
- System Architecture: Develop system architecture that "allows rapid integration of new techniques in a way that preserves system integrity and satisfies ever-increasing performance requirements."
- Human Interface: Develop improved displays of dynamic system

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* Research on this requirement of the NASA systems is particularly important because there is little attention to it elsewhere.

relationships, and use DARPA's extensive work in speech and natural language processing.

SRI's assessment of the highest priority space applications is:

- **satellite servicing;**
- **on-board monitoring & diagnosis;**
- **space manufacturing; and**
- **assembly of space structures.**

SRI cautions against "premature enthusiasm" over expert systems, observing that most expert systems:

- are experimental;
- are not generalizable beyond the original task domain; and
- use very simple knowledge representations.

Further, expert systems programming tools are too immature to be useful for complex problem domains. **Serious advances in knowledge representation and reasoning are the "most important means of enabling automation of space station applications."**

Although SRI presents a detailed R&D agenda, specific funding recommendations are not made. The latter is a dominant issue in the highly resource-constrained environment of the U.S. space station program but its resolution is seen as the joint responsibility of NASA and the Congress.

Methods of managing and coordinating large-scale distributed R&D programs focusing on a singular objective (e.g., space station automation) require careful thought, deep insight, and substantial prior experience. In the best of situations, a substantial measure of good fortune is also required. Cooperation among the agencies comprising the national funders of automation research (including DOD, NASA, and NSF) remains an elusive goal. These issues fall outside SRI's purview, but their appropriate resolution will be key to successfully incorporating advanced A&R into the space station program.

SRI displays a keen sense of the existing state of automation-related technology, as well as current government research programs. Some proposed milestones, particularly the early ones (1986) are too aggressive given current budgets. **The entire program outlined by SRI is of a scale commensurate with the recommendations of the Automation & Robotics Panel (ARP),** to be addressed next. Differences are limited to detail.

The design-for-automation section of the SRI report is particularly relevant to Phase B studies. The other sections are useful as a guide to understanding the intent of the design-for-automation section. **Some of the short term objectives, particularly telepresence and some artificial intelligence work (fault isolation, subsystem control, and procedural planning), are cited as being achievable by IOC, hence are directly relevant to Phase B.**

AUTOMATION AND ROBOTICS PANEL (ARP)

The ARP report presents a comprehensive and challenging program for consideration by NASA and the U.S. Government. It recommends a pragmatic, long-term program of R&D to realize the vision endorsed by the Congress, and it proposes specific recommendations to realize progress not only in the long term, but also for IOC. Rather specific funding recommendations are made. The proposed program of R&D is to reach a level of $190M per year by 1990. A minimum program is viewed to cost $100M per year. At this point, it is important to understand that **the A&R research and development program recommended by the ARP would be limited to the stages from concept to "breadboard" (i.e., laboratory demonstration); the program would not fund the stages from breadboard, through spaceflight demonstrations, to operational use.*** This proviso is in accordance with the ARP's primary thrust of "advancing specific areas of fundamental technology."

As a major goal, the ARP recommends that the space station operate with a very high level of automation by 2010. This goal is to be facilitated by a major emphasis on designing the IOC space station to accommodate growth and evolution of A&R technology. As recommended by the ARP, adequate attention to A&R in the IOC station is to be enforced by grading Phase B contractors on how well they integrate A&R into their overall planning. **A major problem identified by the ARP is a prevailing view within NASA that A&R objectives compete with and are not a part of core space station design objectives.**

Table 2-1 shows the ARP's view of technologies and concepts important to the evolutionary space station.* Table 2-2 shows how these are translated into design features in the IOC space station,* and Table 2-3 suggests pre-IOC demonstrations and milestones to reach the IOC capabilities. The ARP argues that NASA can play a unique

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* The stages of new technology development are customarily defined within NASA as Technological Readiness Levels:

Level 1	Basic principles observed and reported
Level 2	Conceptual design formulated
Level 3	Conceptual design tested analytically or experimentally
Level 4	Critical function/characteristic demonstration
Level 5	Component/breadboard tested in relevant environment
Level 6	Prototype/engineering model tested in relevant environment
Level 7	Engineering model tested in space
Level 8	Full operational capability

* With respect to the entries "Robot accommodations" and "Modularity concepts" in Table 2-1 and the entry "Initial devices and structures that allow for ease of operation, recognition, and movement by robots" in Table 2-2, it should be noted again that any attempt at standardization, at least in the commercial space community, will succeed only through demonstrating that a real benefit will accrue. This will, of course, be evident in inverse proportion to the degree of difficulty (and, hence, the cost) the standardization will entail. The other possibility -- standardization by decree -- could produce, as its major effect, a mass exodus of customers to the European Ariane launcher.

Table 2-1 Suggested pre-IOC A&R Demonstrations and Milestones

	Near-Term: To 1988		Mid-Term: 1989 to 1992 (IOC)	
General		Flight-test some common "off-the-shelf" hardware (e.g., memory drives) to develop simpler flight qualification standards	Demonstrate dexterous end effectors and tools	
Robot Hardware	Terrestrial demos in simulated space environment - Semi-autonomous Space Station assembly - Automated inspection - Autonomous "go-fer"	Begin flight demos in shuttle Complete telerobot compatibility standards for Space Station design	Continue flight of terrestrially demonstrated hardware Demonstrate techniques for in-space parts adaptation/fabrication	"Scars" for hardware implementations after IOC
Sensors	Develop sensors & low level perception systems to support specific requirements of Space Station		Develop special-purpose hardware for sensory data processing	
Controls and Man/Machine Interfaces	Identify A&R human factors concerns	Develop and demonstrate force feedback for Shuttle Remote Manipulator System	Demonstrate robotic control systems pertinent to space environment - Micro-g manipulation - Flexible arms - Execution monitoring with real-time simulation	Demonstrate limited speech control operator interface Demonstrate multi-arm telerobots and robots for internal & EVA applications
Artificial Intelligence and Knowledge Engineering	Lab demos of space applicable early expert systems - Utilities monitor - Life Support System monitor - Data storage/access - Astronaut briefing	Accommodate in space and on the ground CAD databases, describing and integrating Station components from all contractors	Flight demos of early expert systems Demonstrate flexible dynamic simulation using CAD database	Demonstrate expert system applications to - Crew activity planning - Communications monitoring -Fault isolation

Table 2-2 Technologies and Concepts Important to Growth and Evolution of the NASA Space Station

- Natural and efficient man/machine interfaces (e.g., voice and speech comprehension, heads-up displays, supervisory control of robots).
- Robot accommodations (e.g., standard fastenings, bar codes).
- Advanced robot capabilities (e.g., perception, manipulation, judgment, mobility).
- Standard high capacity, redundant, fault-tolerant internal and external communications networks.
- Modularity concepts that facilitate system evolution.
- Standard computer languages.
- Problem-oriented user languages.
- Comprehensive simulation for operational planning and decision making (including parts and system status, scenario testing).
- Integrated computer aided engineering and some on-site fabrication capability.
- Systems that are tolerant and protective of personnel.
- Expert systems and dynamic databases conducive to growth.
- Continuously improved computer systems, including parallel processing, and high speed circuitry.
- Methods for identifying, evaluating, projecting, and displaying effects of rapidly evolving technologies.
- Self evaluating, self repairing life-support and utilities systems with reduced dependence on Earth provisioning.
- Operational policy that utilizes astronauts in increasingly higher levels of creative activity, liberating them from routine functions.

Table 2-3 Features of the IOC

- New ways of promoting the use of state-of-the-art A&R hardware to allow use of evolutionary design of computer and robotics systems.
- A flexible Earth-based computing/network test-bed for developing initial and later generation space station information management systems.
- Selected designs featuring modularity, reserve capacity, flexibility, and standard protocols.
- Initial devices and structures that allow for ease of operation, recognition, and movement by robots; this includes standardized markings (e.g., bar codes), color codes, connectors and other fastenings, and computer/network interfaces.
- Initial use of expert systems for selected tasks such as utilities analysis, fault isolation, environmental monitoring, information retrieval, and astronaut briefing.
- Provisions for obtaining and representing knowledge derived from experience for use in later, more competent expert systems.
- An initial network design and hierarchical computing system that allows for increasing decentralization.
- Selected initial and increasing use of autonomous robots.
- Deliberate accommodation, testing, and use of equipment and procedures developed in terrestrial applications for non-critical functions.

role in national technology development, leading in those areas unique to its national role, leveraging areas which have been identified by others for emphasis, and exploiting technology which will evolve in a natural way because of other factors and interests. Table 2-4 suggests NASA's role in automation-related technologies. Table 2-5 indicates gross funding levels for a mature NASA automation R&D program supporting the space station and national interests, and Figure 2-6 suggests a funding profile to reach this steady-state level. (Note that the funding levels these tables are derived from estimates of the manpower required to accomplish the tasks.)

The ARP recommends that NASA establish an organizational structure, independent of the space station program, to manage the technology program, and proposes that NASA actively promote interactions among and benefits to national communities in order to realize the possibilities foreseen by the Congress.

The ARP recommends a very aggressive and technically exciting program of automation-related R&D. If NASA is to implement it, a major change in NASA's operating mode and national role would have to take place. The space station program, as envisioned by the ARP, could become the centerpiece of a national thrust toward advanced automation, and NASA's role would broaden considerably beyond "simply" building another space-based resource. This twofold result appears to be the thrust of Congressional interest, and it poses major issues to NASA.

How should NASA organize to meet competing objectives of a successful space station and advancing industrial automation technology? Where will the funding come from? NASA technology programs are typically small. **The ARP report recommends a focused program roughly ten times larger than prior focused R&D programs NASA has conducted.** Does the agency have the capability to manage such a large-scale R&D program? Does it have the desire? Can it avoid the temptation to redirect R&D funds to another project experiencing funding or schedule problems? Can it avoid the temptation to pursue peripheral interests and favorite projects, or will the agency have

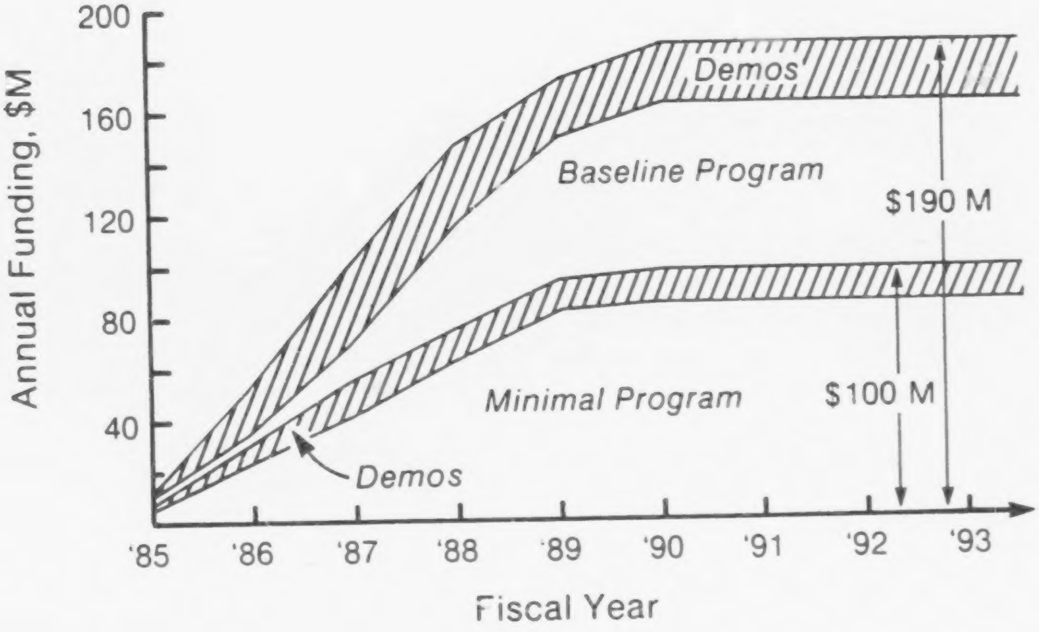
Table 2-4 Automation and Robotics Technology Advancement Program

Class	Man/Machine-Robotics	Information Management	Communication & Mechanical Infrastructure
NASA must *lead*[*]	Space Manipulators Materials Handling Technologies Robot Mobility in Space Man/Machine Interfaces	Expert System Mission & Payload Control, Planning & Directing "Smart" Simulations Fault-Tolerant, Reliable Software Tools CAE Standards Software Language Standards Automation Design for Integrating Technology	Lightweight Structure & Assembly Spare Parts & Repair Technology Fluids Transfer Technologies
NASA applies *leverage*	Robot Sensors/Integration Reconfigurable & Repairable Robots High-Level Robot Programming Language	Space-Related Custom Hardware Communications Networks Distributed Large-Scale Databases CAD-Directed Programming Knowledge-Based System Development Sensing Algorithms Real-Time Systems Facility "Seed" Funding	New Fabrication Technologies
NASA can *exploit* (examples)	Terrestrial Robots and Manipulators Lightweight Motors	Computer Architecture Chip Technologies Speech Technologies	Local Area Networking Display Technologies High Bandwith Technologies Communication Technologies

Table 2-5 Automation and Robotics Technology Program Cost Summary

	Annual Funding Levels ($M/yr) *Baseline Program* *Research*	 *Demos*
NASA Leads:		
Man/Machine-Robotics	51	10
Information Management	26	4
NASA Applies Leverage:		
Man/Machine-Robotics	25	4
Information Management	31	7
NASA Exploits (Buys):		
Man/Machine-Robotics	< 1	< 1
Information Management	4	< 1
Infrastructure Technical Adjustment†	23	5
Program Totals	160	30
Combined Elements	190	

Figure 2-6 A&R Technology Advancement Program Funding Guidelines



the spirit to reshape its programs in the interests of long-term national and agency needs? Can appropriate incentives be provided the space station contractors so that the automation recommendations will not be neglected?

The ARP study results are realistic in terms of the agenda the panel set for itself. Whether this agenda matches the agenda of the Congress is likely to remain a subject of discussion for some time.

Most ARP members have had substantial experience with similar programs (e.g., the DARPA Strategic Computing Program), and could bring it to bear on the space station automation problem. Realistic funding estimates were a paramount concern of the panel. However, whether these estimates are realistic for NASA is another issue entirely.

The ARP report is directly relevant to Phase B and, presumably, is "required reading" for all participants in Phase B studies. It provides the most comprehensive available view of the far-term potential of A&R both to increase the viability of the space station and to provide important benefits on Earth, as well as the near-term steps to reach that potential.

NASA: ADVANCED TECHNOLOGY ADVISORY COMMITTEE (ATAC)

The ATAC report comprises the official NASA interpretation of all of the space station automation studies. It integrates the collective findings of the study participants into a self-consistent view and translates these findings into recommended NASA policy for space station automation and robotics.

The ATAC report enumerates the potential benefits to be derived from A&R technology developed for the space station. Benefits to space activities include:

- increased productivity;

- increased responsiveness to innovation;
- lower cost of operations;
- improved reliability;
- greater autonomy;
- greater capability; and
- decreased exposure of crew to hazardous situations.

Benefits to the U.S. economy include:

- increased suitability of space station for commercial ventures, and
- spin-off of space technology to terrestrial applications.

The following eight policy statements are recommended by the ATAC for the basic space station program:

1. Automation and robotics should be a significant element of the space station program.
2. The initial space station should be designed to accommodate evolution and growth in automation and robotics.*
3. The initial space station should utilize significant elements of automation and robotics technology.
4. Criteria for the incorporation of A&R technology should be developed and promulgated.
5. Verification of the performance of automated equipment should be stressed, including terrestrial and space demonstrations to validate technology for space station use.
6. Maximum use should be made of technology developed for industry and Government.
7. The techniques of automation should be used to enhance NASA's management capability.**
8. NASA should provide the measures and assessments to verify the inclusion of

automation and robotics in the space station.

The ATAC committee additionally recommended the following five policy statements, contingent upon an augmented A&R program:

9. The initial space station should utilize as much automation and robotics technology as time and resources permit.
10. An evolutionary station should achieve, in stages, a very high level of advanced automation.
11. An aggressive program of long-range technology advancement should be pursued, recognizing areas in which NASA must lead, provide leverage for, or exploit developments.
12. A vigorous program of technology transfer to U.S. industries and research and development communities should be pursued.
13. Satellites and their payloads accessible from space station should be designed, as far as possible, to be serviced and repaired by robots.*

A comparison of the first eight with the last five ATAC policy statements reveals that, in the space station program as currently defined, no basic research aimed at advancing the state of the art in A&R is contemplated.** The ATAC report recommends an aggressive technology development and deployment program for the space station only if additional funds are appropriated. **That is, the ATAC recommends that the space station program commit funds to A&R only at Technological Readiness Levels 5-8.**

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* There is little doubt that this is the single most important recommendation.

** It is possible that the most important payoff from pushing A&R in the Space Station Program may not be in enhanced space station performance nor in direct terrestrial spinoffs, but in expert-system-based testing, software verification and validation, design and requirements databases, and intelligent management tools (schedule, costing, and configuration management).

* As noted earlier, this approach may be an example of putting the cart before the horse. Space commercialization may in fact be set back if there is a mandate that all satellites will, in their design, make up for the shortcomings of the single, officially recognized robot servicer. A more reasonable objective might be to advance the state of the art in A&R to the point that any satellite designed with reasonable interfaces can be serviced with the space station system. If a given company designs and flies a highly modular satellite for use with a simple robotic servicer, so much the better, but many satellites cannot be produced economically with such a restriction.

** Some within NASA argue that the state of the art in A&R may be advanced by applied R&D as well as by basic research. While this may be true in particular

Tables 2-6 and 2-7 list the proposed goals for the IOC space station and the evolutionary space station, respectively. It is clear from these lists that the ATAC considers A&R to be pervasive technologies for the space station.

The ATAC argues that A&R cannot be tacked onto the space station after the fact. The space station must be designed from the start to support and be supported by the advancement of A&R. The ATAC proposes design guidelines to facilitate incorporation of evolving technology, including the following:

- design the environment to accommodate commercial and off-the-shelf technology;
- incorporate standard interfaces;
- design for ease of assembly and servicing;
- design for ease of identification and accessibility;
- design for autonomy of routine deterministic operations;
- incorporate an evolutionary computer system architecture;
- incorporate Computer-aided design/Computer-aided engineering (CAD/CAE) for accommodating artificial intelligence and robotics technology; and
- design for ease of communication and cooperation with intelligent systems.

The ATAC also addressed potential commercial application areas which could benefit from A&R technology developed for the space station.* These technology transfer opportunities are summarized in Table 2-8.

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instances, this report, and the great majority of its reviewers, takes the position that, overall, a continuous flow of basic research results is needed to maintain a steady advance in the state of the art.

* The ATAC report makes many other recommendations in a variety of other categories as well. This report does not attempt to review them all.

Table 2-6 Proposed Goals for Automation and Robotics Applications Initial Space Station

- **Electrical Power**

  Controllers enhanced by expert systems for
  - Load distribution and switching
  - Solar array orientation
  - Trend analysis
  - Fault diagnosis

- **Guidance, Navigation, and Control**

  Expert systems for
  - Station attitude control
  - Experiment pointing
  - Orbital maintenance and reboost
  - Rendezvous navigation
  - Fault diagnosis

- **Communication and Tracking**

  An executive enhanced by expert systems for
  - Communication scheduling
  - Rendezvous tracking
  - Data rate selection
  - Antenna pointing

- Information and Data Management

  An executive enhanced by expert systems for control of
  - Subsystem statusing
  - Trend analysis
  - Fault diagnosis
  - Redundancy and configuration management
  - Data base management

- **Environmental Control and Life Support**

  Controllers enhanced by expert systems for
  - Trend analysis
  - Fault diagnosis
  - Crew alarm
  - Station atmosphere monitoring and control
  - Hyperbaric chamber

- **General**

  Teleoperation of mobile remote manipulator with collision avoidance

  Mobile multiple-arm robot with dextrous manipulators to inspect and exchange orbital replacable units

  Systems designed to be serviced, maintained, and repaired by robots

  Primary station control in space with appropriate backup

Table 2-7 Proposed Goals for Advanced Automation and Robotics Applications

Evolutionary Space Station

- **Propulsion**

  An intelligent controller for
  - Fuel distribution and management
  - Leak detection and evaluation

- **Electrical Power**

  An autonomous intelligent controller for
  - Power management
  - Fault detection and isolation
  - Maintenance scheduling

- **Guidance, Navigation, and Control**

  An intelligent controller for
  - Fully automatic rendezvous and docking
  - Space traffic control
  - Remotely piloted vehicles
  - Collision avoidance

- **Communication and Tracking**

  An intelligent system for
  - Automatic planning
  - Tracking multiple vehicles
  - Scheduling bulk data storage for communications blackouts
  - Detection, identification, and characterization of general targets

- **Information and Data Management**

  A intelligent system for
  - Fault detection, isolation, and repair
  - Natural language interface with crew

  A data base manager for
  - CAD/CAE bulk data storage facility
  - Retrieval and routing to requestors

- **Environmental Control and Life Support**

  An intelligent controller for
  - Ensuring fail-safe/fail-operational modes
  - Fault detection and isolation
  - Chemical analysis of air and water
  - Toxic gas analysis

- **Habitability**

  An intelligent system for
  - Health maintenance
  - Speech interpretation and synthesis
  - Physiological monitoring
  - Automated medical decisions
  - Trend analysis

- **Structures and Mechanisms**

  Advanced work station
  Intelligent actuators
  Teleoperators

- **Orbiting Platforms**

  An intelligent system for
  - Process control
  - Maintenance control
  - Planning and trend analysis

- **General**

  Robots for
  - Inspection, maintenance, refurbishment, and repair
  - Fuel and materials transfer
  - Detecting hazardous leaks
  - Satellite retrieval and servicing

Table 2-8 Potential Intelligent Robot Applications in the U.S. Economy

Settings	**Uses**
Factories (manufacturing, light industry)	Welding, machining, painting, molding, assembly, inspection, repair, loading, packaging
Offices and institutions (hospitals, schools, prisons)	Distribution (mail, supplies, food), cleaning (floors, windows, trash)
Undersea	Surveying, search and rescue, cable laying, construction, extraction
Mining; oil and gas	Extracting, drilling, rescue (firefighting, boring), processing
Nuclear power plants	Maintenance, emergency operations
Agriculture	Harvesting, planting, irrigation, fertilizing, weed and pest control
Construction	Excavations, structure erection and demolition
Home	Aiding elderly or handicapped

The ATAC report recommends NASA policies that are designed to ensure appropriate consideration of automation and robotics technology in the space station program. These policy recommendations are well-conceived and carefully thought through, and represent a major step toward satisfying the requirements of P.L. 98-371. However, insofar as Report 98-506 records the spirit behind P.L. 98-371, the ATAC report falls short of the mark in not emphasizing the importance of substantial NASA A&R research in Technology Readiness Levels 1-4.

Although at the present time, the ATAC recommendations seem to have become NASA policy, important questions remain: What steps are being taken to translate these policy statements into action plans? Where does the responsibility lie to ensure incorporation of these plans in the space station design?

The ATAC has a major oversight and reporting responsibility to suggest and monitor A&R initiatives for the space station program. However, in order to ensure that A&R is being successfully addressed in that program, ATAC may need even more technical expertise, program insight, and management clout than it has currently.

These are highly time-critical issues. Substantial momentum was generated by the automation studies. This momentum is likely to dissipate unless strong and definitive leadership is demonstrated by NASA management and Congress.

The ATAC report is based directly on the reports of the aerospace contractors, SRI International, and the ARP. To the extent that the conclusions reached in those reports are realistic, the ATAC report is realistic. The major contribution of the ATAC report is the translation of those findings into agency policy recommendations. Not only are these recommendations realistic, but their implementation is necessary if advanced levels of automation and robotics in the space station program are to be achieved and the Congressional mandate to enhance "the Nation's scientific and technical base leading to more productive industries on Earth" is to be carried out.

The ATAC report is not merely relevant, but vital to Phase B. It recommends a policy which, if fully implemented, could go far toward ensuring that the design studies leading ultimately to the actual NASA space station will be responsive to A&R possibilities in Phase B and beyond.

McDONNELL DOUGLAS STUDY

The Human Role in Space, (THURIS)

In October of 1984, McDonnell Douglas Astronautics Company (McDAC) completed a study entitled, "The Human Role in Space" (THURIS). This study was not conducted as part of the space station automation studies, but is relevant nonetheless.

The perspective of the THURIS study is quite different from those of the other studies. Its stated objectives were:

- to investigate the role and degree of direct involvement required of humans in future space missions,
- to establish criteria for allocating functional activities between humans and machines, and
- to investigate the technology requirements, economics, and benefits derived from a human presence in space.

McDonnell Douglas performed a comprehensive analysis of the decision elements which must be considered in establishing functional allocations between humans and machines. The THURIS study, beginning with the observation that there is "no such thing as an unmanned system," defines classes of interaction between humans and machines. These are shown in Table 2-9, and clearly illustrate the spectrum of operational modes from manual operation through autonomous operation.

The THURIS study examined a series of historical, current, and proposed space

Table 2-9 Categories of Human-Machine Interaction

Manual	Unaided IVA/EVA, with simple (unpowered) hand tools
Supported	Requires use of supporting machinery or facilities to accomplish assigned tasks (e.g., manned maneuvering units and foot restraint devices)
Augmented	Amplification of human sensory or motor capabilities (powered tools, exo-skeletons, microscopes, etc.)
Teleoperated	Use of remotely controlled sensors and actuators allowing the human presence to be removed from the work site (remote manipulator systems, teleoperators, telefactors)
Supervised	Replacement of direct manual control of system operation with computer-directed functions although maintaining humans in supervisory control
Independent	Basically self-actuating, self-healing, independent operations minimizing requirement for direct human intervention (dependent on automation and artifical intelligence)

missions to develop a list of 37 "unique generic space activities" which comprise the current repertoire of things we do or want to do in space. Table 2-10 lists these activities. Table 2-11 summarizes McDAC's assessment of the role of the human with respect to each of these activities. The highlighted boxes identify activities judged by McDAC to benefit particularly from direct human involvement.

The McDonell Douglas cost model is used to estimate costs of performing activities in space. Alternative human/machine interaction modes are considered for each activity as a function of the number of repetitions of the activity.* Costs for productive crew activities are estimated to be in excess of $32K/man-hr (in FY-1984 dollars). Figure 2-7 illustrates one of these analyses. Cumulative costs for automating different activities to increasing levels vary greatly among activities, but most specific activities must be repeated on the order of a thousand times before higher levels of automation displace manual operation strictly on the basis of cost (though there may even be some one-time-only activities which could qualify for automation on the basis of cost).

Although automation of individual, isolated activities is probably not justifiable solely on the basis of cost, synergy of equipment among activities can be expected to justify such an investment when mission-level objectives are considered. Figure 2-8 illustrates how these economies operate for the same activity displayed in figure 2-7. When 16 activities are considered as a group, taking advantage of expected levels of commonality of equipment required to implement these activities, only 300 repetitions of activity 29 over the life of the space station are required to justify on-orbit supervised control.

The THURIS study includes an analysis of the time required for technology to evolve in practice from the laboratory to operational use. Periods of twenty years are

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* It must be noted, however, that some of the activities for which the human presence is deemed essential (e.g., #4, "Apply/remove biomedical sensors," and #35, "Surgical manipulations") would not be necessary if human beings were not present.

Table 2-10 Generic Space Activities

1. *Activate/Initiate System Operation:* Those events and/or command sequences involved in the activation or initialization of a space-based system or subsystem.

2. *Adjust/Align Elements:* Those adjustment activities involved in such operations as alignment of optical elements, fine tuning of precision electronic equipment, antenna pointing, and remote camera focusing operations.

3. *Allocate/Assign/Distribute:* Those activities involving the reallocation or redistribution of resources: e.g., the redistribution of power, coolant flow, etc. to sensitive subsystem equipment to reflect operational needs or contingency operations.

4. *Apply/Remove Biomedical Sensor:* Those unique activities associated with the installation/removal and cleaning of sensors used to obtain biomedical data from a test subject.

5. *Communicate Information:* Those activities involving the establishment of the communications link and the transmision of information from one source to another. It includes the verbal or visual interchange between two crewmen as well as the electronic transference of scientific information from a space probe to a terrestrial-based user.

6. *Compensatory Tracking:* Those activities involving continuous control adjustments to null an error signal against a fixed reference.

7. *Compute Data:* Those activities requiring a mechanized form of data processing, such as in structural analyses, computation of positions of celestial bodies, or other forms of numerical computations.

8. *Confirm/Verify Procedures/Schedules/Operations:* Those activities involving the assessment of whether or not a previous event has in fact been accomplished (such as a system verification or checkout), or a procedure satisfied, or a schedule met.

9. *Connect/Disconnect Electrical Interface:* Those activities requiring the completion or termination of an electrical interface. They may involve use of blind-mated/self-aligning connectors, multiturn screw-drive interface plates, or similar devices.

10. *Connect/Disconnect Fluid Interface:* Those activities requiring the completion or termination of a fluid interface. They may involve use of a simple plug-in, sleeve-lock connection, multiturn screw-drive interface plates, or similar devices.

11. *Correlate Data:* Those activities involving the identification of positive or negative relationships or commonalities among data sets, such as organizational structures, characteristics, or processes.

12. *Deactivate/Terminate System Operation:* Those events and/or command sequences involved in the termination or deactivation of a space-based system or subsystem.

13. *Decode/Encode Data:* Those activities involving the conversion of data into either its original form or into a form compatible for transmission: e.g., converting transmitted digitized data into its original analog form or digitizing analog data for transmission to the ground station.

14. *Define Procedures/Schedules/Operations:* Those activities involving logical deductions or convergent production leading to development of procedures, schedules, or operations with predictable outcomes.

15. *Deploy/Retract Appendage:* Those activities associated with the extension of a hardware element to a position where its assigned function can be realized, or conversely, the stowing of that hardware element based on task completion or safety considerations.

16. *Detect Change in State or Condition:* Those activities wherein the departure of a parameter from its original or reference state or condition is required to be sensed or observed.

17. *Display Data:* Those activities involving the presentation of information/data by visual, auditory, or tactual means.

18. *Gather/Replace Tools/Equipment:* Those activities involved in the obtaining or returning of tools or equipment used to perform a specific task, such as collecting or replacing maintenance tools or donning/doffing the Manned Maneuvering Unit.

19. *Handle/Inspect/Examine Living Organisms:* Those activities involving the unique operations associated with working with living organisms. These activities involve the manipulation and general handling of animals, ranging from stroking to inspecting or examining anatomical characteristics.

20. *Implement Procedures/Schedules:* Those activities involving the instituting and carrying out of procedures or schedules (such as updating a mission model/schedule) as distinguished from activating or initiating system operations.

21. *Information Processing:* Those activities involving the categorizing, extracting, interpolating, itemizing, tabulating, or translating of information.

22. *Inspect/Observe:* Those activities involving the critical appraisal of events or objects. They may include the verification or identification of a particular elements, such as damage inspection of a returning orbital test vehicle, observation and identification of a celestial object, or behavior of a living organism.

23. *Measure (Scale) Physical Dimensions:* Those activities involving the estimation or appraisal of a dimension against a graduated standard or criterion.

24. *Plot Data:* Those activities involving the mapping, displaying, or locating of data by means of a specified coordinate system.

25. *Position Module:* Those activities involving the positioning of a component into a desired orientation: e.g., installing a new component, or tilting a payload into its launch orientation.

26. *Precision Manipulation of Objects:* Those activities involving tasks that require a high degree of manual dexterity, such as the assembly/disassembly of small intricate mechanisms, or the installation of measurement sensors, i.e., strain gages, thermocouples, etc.

27. *Problem Solving/Decision Making/Data Analysis:* Those judgmental and sometimes creative activities involving the drawing of inferences or conclusions through the use of cognition, convergent or divergent production, memory, and comparative evaluation. Functions to be performed may include analyzing, calculating, choosing, comparing, estimating, or planning.

28. *Pursuit Tracking:* Those activities involving continuous control adjustment to match actual and desired signals when the desired or reference signal is continually changing.

29. *Release/Secure Mechanical Interface:* Those activities involving the manipulation of a mechanical interface ranging from a simple one-handed, over-center latch application to a high-torque, multiturn threaded fastener. May involve manipulation of multiple fasteners arranged in various patterns or configurations.

30. *Remove Module:* Those activities involving the physical extraction or removal of a component after the mechanical, electrical, or thermal interfaces have been released or disconnected.

31. *Remove/Replace Covering:* Those activities involving the removal or reinstallation of an access covering or a protective covering as required to gain access to system elements or to cover them up upon completion of the work.

32. *Replace/Clean Surface Coatings:* Those unique activities involving the restoration of a degraded/contaminated surface coating, such as replacing a radiator's thermal coating or cleaning an optical system's viewing surface.

33. *Replenish Materials:* Those activities involving the resupplying of consumables, such as refueling a spacecraft, recharging an optics cryo-based cooling system, or providing food supplies to an animal holding facility.

34. *Store/Record Element:* Those activities involving the recording or storage of items for both short-term and long-term periods: e.g., recording/storage of experimental data or the temporary storage of a biomedical sample.

35. *Surgical Manipulations:* Those activities, such as a surgical procedure or a dissection, including tissue sample acquisitions, that require a high degree of skill and knowledge as well as manual dexterity.

36. *Transport Loaded:* Those activities involving the conveying of a physical object by some transportation device from one location to another: e.g., the transporting of a component via a crewman or a remote manipulator system.

37. *Transport Unloaded:* Those activities involving the movements of an unloaded individual or device from one location to another: e.g., the movement of a crewman to a worksite without carrying tools or equipment, or the movement of a remote manipulator system with nothing attached.

Table 2-11 Human Role in Space Activities (p.1 of 2)

No.	Generic space activity	Key capabilities utilized in man's participation	Benefit of man's onboard participation			Overall benefit from man's onboard participation	Rationale
			Equipment can be eliminated	Performance of activity is improved	Probability of mission success is increased		
1	Activate/initiate system operation	Evaluation Vision Manipulation	Minimal	In some cases	Negligible	Not significant	Automatically activated systems will predominate
2	Adjust/align elements	Vision Cognition Evaluation	Yes	In some cases	No	Beneficial	Most alignment operations within man's capabilities
3	Allocate/assign/distribute	Cognition Convergent Prod.	No	In some cases	Minimal	Not significant	Primarily automated operations
4	Apply/remove biomedical sensors	Cognition Manipulation	Not applicable	Yes	Yes	Essential	Operations cannot easily be automated
5	Communicate information	Cognition Vision	No	In some cases	No	Not significant	Communication link established automatically
6	Compensatory tracking	Cognition Evaluation Vision Manipulation	Minimal	No	Minimal	Not significant	Highly dependent on nature of tracking task. Nullifying error signal could be automatic
7	Compute data	Cognition Evaluation	No	No	Minimal	Not significant	Man will play negligible role in most data computation
8	Confirm/verify/procedures/schedules/operations	Cognition Evaluation	No	No	Minimal	Not significant	Man would usually function in a backup role only
9	Connect/disconnect electrical interfaces	Vision Gross Motor Act. Manipulation Evaluation	Yes	Yes	Yes	Beneficial to essential	Typical utilization of man's basic capabilities
10	Connect/disconnect fluid interfaces	Vision Gross Motor Act. Manipulation Evaluation	Yes	Yes	Yes	Beneficial to essential	Typical utilization of man's basic capabilities
11	Correlate data	Cognition Evaluation	No	In some cases	Minimal	Not significant	Man would usually function in a backup role only
12	Deactivate/terminate system operation	Manipulation Vision Evaluation	Minimal	In some cases	Negligible	Not significant	Automatically deactivated systems will be the norm
13	Decode/encode data	Cognition Convergent Prod.	No	No	No	Not significant	Computer function only
14	Define procedures/schedules/operations	Cognition Divergent Prod.	Yes	Yes	Yes	Essential	Activity is wholly dependent on man's intellectual capabilities
15	Deploy/retract appendage	Vision Gross Motor Act.	Yes	In some cases	In some cases	Beneficial	Seldom repeated activities are poor candidates for automation
16	Detect change in state or condition	Cognition Evaluation Vision	No	In some cases	In some cases	Beneficial or essential	Strongly dependent on characteristics of activity
17	Display data	Cognition Evaluation	No	Yes	Yes	Beneficial to essential	Man important in selection of data to be displayed
18	Gather/replace tools/equipment	Cognition	Yes	Yes	Minimal	Beneficial to essential	Man can vary tool selection with respect to task
19	Handle/inspect/examine living organisms	Cognition Vision Manipulation	Not applicable	Yes	Yes	Essential	Activity cannot be automated in most cases
20	Implement procedures/schedules	Cognition Evaluation Convergent Prod.	Not applicable	Yes	Yes	Essential	Activity dependent on man's involvement by definition
21	Information processing	Cognition Evaluation	Minimal	Yes	Yes	Beneficial to essential	Essential interaction between man and computer

Table 2-11 Human Role in Space Activities (p. 2 of 2)

No.	Generic space activity	Key capabilities utilized in man's participation	Benefit of man's onboard participation			Overall benefit from man's onboard participation	Rationale
			Equipment can be eliminated	Performance of activity is improved	Probability of mission success is increased		
22	Inspect/observe	Vision Cognition Evaluation Divergent Prod.	Yes	Yes	Yes	Highly beneficial	Man's selective observations superior to automated monitoring
23	Measure (scale) physical dimensions	Vision Evaluation	In some cases	No	In some cases	Beneficial (in some cases	Man is best alternative in some situations
24	Plot data	Cognition	No	Minimal	No	Not significant	Primarily a computer function
25	Position module	Vision Evaluation Gross Motor Act.	In some cases	In some cases	In some cases	Beneficial for some activities	Man's benefit highly dependent on type of activity
26	Precision manipulation of objects	Vision Manipulation Cognition	Yes	Yes	Yes	Most often essential	Man's manipulative skills cannot be duplicated by automatic devices
27	Problem solving/ decision making/data analysis	Cognition Divergent Prod. Convergent Prod. Evaluation	Yes	Yes	Yes	Essential	Man essential by definition
28	Pursuit tracking	Cognition Manipulation	Minimal	Yes	Minimal	Could be significant	Dependent on specific tracking task
29	Release/secure mechanical interface	Vision Gross Motor Act. Manipulation Evaluation	Yes	Yes	Yes	Beneficial to essential	Exemplary utilization of man's capabilities in space activity
30	Remove module	Vision Evaluation Gross Motor Act.	In some cases	In some cases	In some case	Beneficial for some mission activities	Man's benefit highly dependent on type of activity
31	Remove/replace covering	Vision Evaluation Gross Motor Act.	In some cases	In some cases	In some cases	Beneficial for some cover removal/ replacement activities	Man's benefit highly dependent on task characteristics
32	Replace/clean surface coatings	Vision Evaluation Gross Motor Act.	Yes	Yes	Yes	Beneficial to essential	Infrequency of activity negates automation
33	Replenish materials	Vision Evaluation Gross Motor Act.	Yes	In some cases	Yes	Beneficial to essential	Degree of benefit is dependent on nature of task
34	Store/record element	Cognition	No	No	No	Not significant	Man's participation of benefit only in isolated cases
35	Surgical manipulations	Vision Manipulation Cognition	Not applicable	Yes	Yes	Essential	Activity not appropriate for automation
36/ 37	Transport loaded or unloaded	Vision Cognition Gross Motor Act.	In some cases	In some cases	In some cases	Dependent on characteristics of task	Characteristics of tasks can vary extensively for this activity

Shaded activities are those where direct human participation is considered most beneficial or essential

Figure 2-7 Activity 29 Release/Secure Mechanical Interface (Cumulative Cost Versus Number of Times Activity is Performed)

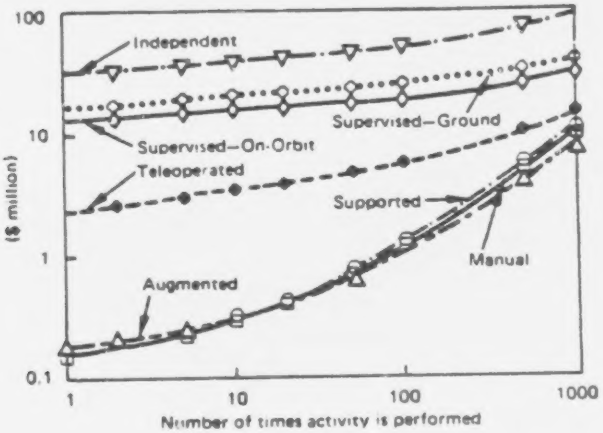
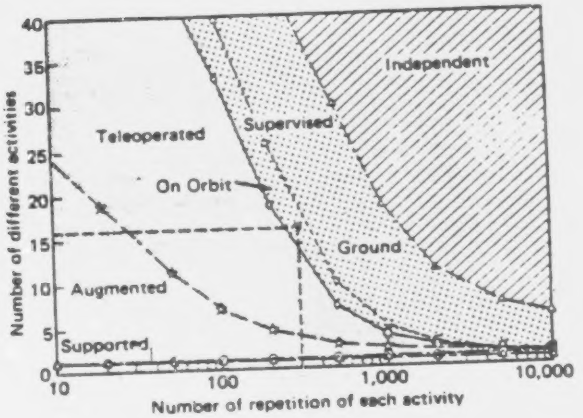


Table 2-11 Human Role in Space Activities (p. 2 of 2)

No.	Generic space activity	Key capabilities utilized in man's participation	Benefit of man's onboard participation			Overall benefit from man's onboard participation	Rationale
			Equipment can be eliminated	Performance of activity is improved	Probability of mission success is increased		
22	Inspect/observe	Vision Cognition Evaluation Divergent Prod.	Yes	Yes	Yes	Highly beneficial	Man's selective observations superior to automated monitoring
23	Measure (scale) physical dimensions	Vision Evaluation	In some cases	No	In some cases	Beneficial (in some cases	Man is best alternative in some situations
24	Plot data	Cognition	No	Minimal	No	Not significant	Primarily a computer function
25	Position module	Vision Evaluation Gross Motor Act.	In some cases	In some cases	In some cases	Beneficial for some activities	Man's benefit highly dependent on type of activity
26	Precision manipulation of objects	Vision Manipulation Cognition	Yes	Yes	Yes	Most often essential	Man's manipulative skills cannot be duplicated by automatic devices
27	Problem solving/ decision making/data analysis	Cognition Divergent Prod. Convergent Prod. Evaluation	Yes	Yes	Yes	Essential	Man essential by definition
28	Pursuit tracking	Cognition Manipulation	Minimal	Yes	Minimal	Could be significant	Dependent on specific tracking task
29	Release/secure mechanical interface	Vision Gross Motor Act. Manipulation Evaluation	Yes	Yes	Yes	Beneficial to essential	Exemplary utilization of man's capabilities in space activity
30	Remove module	Vision Evaluation Gross Motor Act.	In some cases	In some cases	In some case	Beneficial for some mission activities	Man's benefit highly dependent on type of activity
31	Remove/replace covering	Vision Evaluation Gross Motor Act.	In some cases	In some cases	In some cases	Beneficial for some cover removal/ replacement activities	Man's benefit highly dependent on task characteristics
32	Replace/clean surface coatings	Vision Evaluation Gross Motor Act.	Yes	Yes	Yes	Beneficial to essential	Infrequency of activity negates automation
33	Replenish materials	Vision Evaluation Gross Motor Act.	Yes	In some cases	Yes	Beneficial to essential	Degree of benefit is dependent on nature of task
34	Store/record element	Cognition	No	No	No	Not significant	Man's participation of benefit only in isolated cases
35	Surgical manipulations	Vision Manipulation Cognition	Not applicable	Yes	Yes	Essential	Activity not appropriate for automation
36/ 37	Transport loaded or unloaded	Vision Cognition Gross Motor Act.	In some cases	In some cases	In some cases	Dependent on characteristics of task	Characteristics of tasks can vary extensively for this activity

Shaded activities are those where direct human participation is considered most beneficial or essential

Figure 2-8 Effects of Activity Synergy on Operating Modes for Activity 29



not unusual. This phenomenon has also been observed and reported in a recent study performed for the DOD by the Institute for Defense Analysis. Figure 2-9 summarizes McDonnell Douglas' analysis of this transition process. The major challenge is to make sequences for space developments no worse than for terrestrial.*

McDonnell Douglas recommends research and technology development efforts focusing on visual displays, human incident performance analysis, human productivity measurement, and long-term improved understanding of the nature of human intelligence.

The THURIS study also includes a step-by-step decision guide to assist space station designers in allocating functional activities between humans and machines.

The THURIS study articulates automation-related costs as they trade off against operational mode, and suggests a decision process by which issues of automation versus direct human involvement can be resolved. The trade-offs presented require deep insight into actual cost figures and mission models. However, applying these results quantitatively to the design of the space station may be difficult, if not impossible, for the process depends critically on information which cannot be accurately forecast. It is unreasonable to expect anyone to be able to estimate precisely how many repetitions of any activity will be performed over the life of the space station. McDonnell Douglas has found, however, that once an operational scenario has been well defined, it is possible to make reasonable estimates of the number of repetitions of any activity per unit time (e.g., repetitions per year or per 5-year period). This, in turn, has permitted McDonnell Douglas to make, even in a conceptual design phase, comparative judgments of the value of the alternative implementation modes.**

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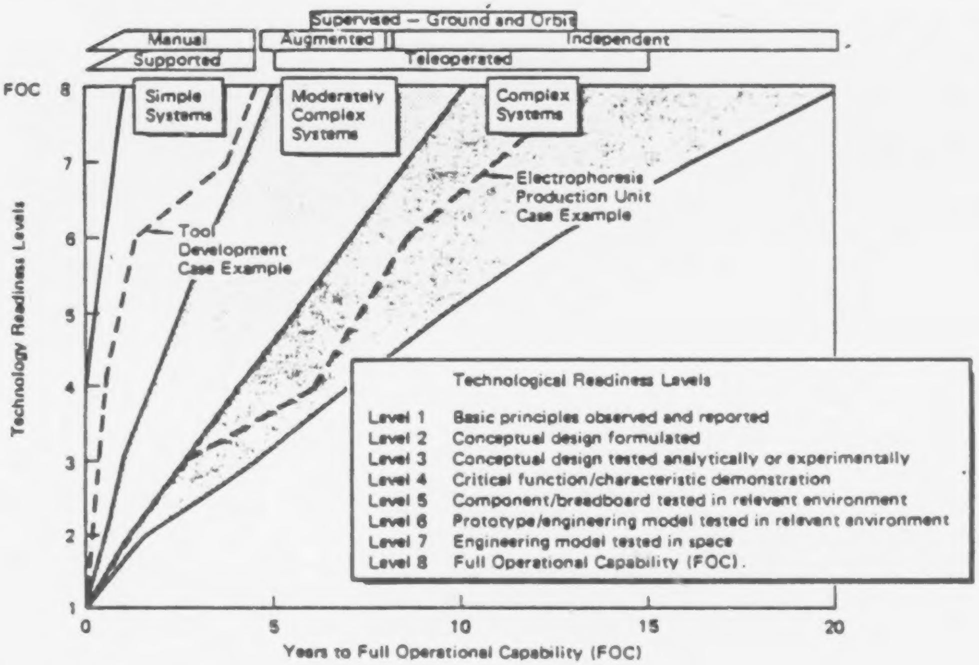
* At $32,000 per man-hour, the cost in space is as much as 2000 times that for comparable activities on the surface. To reduce space costs to match surface costs within 20 years would require an annual reduction in space costs by approximately 50% per year, compounded annually.

** The phrasing of the question is important. For instance, if you ask someone how many razor blades she uses per year, she probably would not be able to provide an accurate answer quickly. If you ask her how often she changes the blade in her

Figure 2-9 Time Required to Reach Various Technology Readiness Levels



Technological Readiness Levels

Level 1	Basic principles observed and reported
Level 2	Conceptual design formulated
Level 3	Conceptual design tested analytically or experimentally
Level 4	Critical function/characteristic demonstration
Level 5	Component/breadboard tested in relevant environment
Level 6	Prototype/engineering model tested in relevant environment
Level 7	Engineering model tested in space
Level 8	Full Operational Capability (FOC).

In any case, the model presented is extremely useful for gaining qualitative insight into the alternatives and for establishing some bounds on cost estimates. Although much work remains to be done in this area, THURIS provides the most complete, objective, and rigorous trade-off analysis to date addressing the relative roles of humans and automated systems in space.

The THURIS study focuses on cost as the objective function; it does not attempt to measure value. In a highly resource-limited space station with a small number of crew members, one would expect their value greatly to exceed their cost. Therefore, it is not clear that the cost of human operations in space should be the dominant decision criterion.

One criticism of the THURIS study has been that it may be too focused on how particular example tasks might be done "by hand" versus by machine. However, spectacular advances in industrial automation occur when particular manipulative tasks are eliminated. For example, when hundreds of discrete components are replaced by one monolithic circuit, manipulation is radically reduced. Similar results are now being sought in AI for the elimination or reduction of programming. In order to make progress in these areas, NASA cannot simply rely on the Level C contractors. Rather, NASA Levels B anc C could be required to give particular attention to reducing the number of discrete space components and to designing space operations so as to minimize manipulation and programming.

The THURIS study is as realistic as the quality of the models used, the validity of the assumptions, and the accuracy of the data. It appears that the model is based on sound principles and has matured to the point of corporate acceptance within McDonnell Douglas. Nevertheless, the validity of the assumptions and the accuracy of the data used should be independently verified before the results are used to make space station design

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razor, she can probably give an accurate answer immediately. From the latter answer, the answer to the former question can be readily calculated.

decisions.

The THURIS study is highly relevant to Phase B design studies. It provides the most rigorous trade-off yet of design decisions that are central to space station automation and robotics.

CHAPTER 3

A&R AND SPACE STATION PHASE B PLANNING

As the space station program completes the first quarter of Phase B planning, the relevant issue becomes whether and, if so, to what extent, the results of the A&R studies are actually being integrated into the mainstream program. This section of the report addresses the progress of such integration. **One basic conclusion is inescapable: except in a few isolated cases, the space station program, as presently configured, will not be a vehicle for advancing the state of the art in A&R.**

NASA'S A&R IMPLEMENTATION PLAN FOR PHASE B

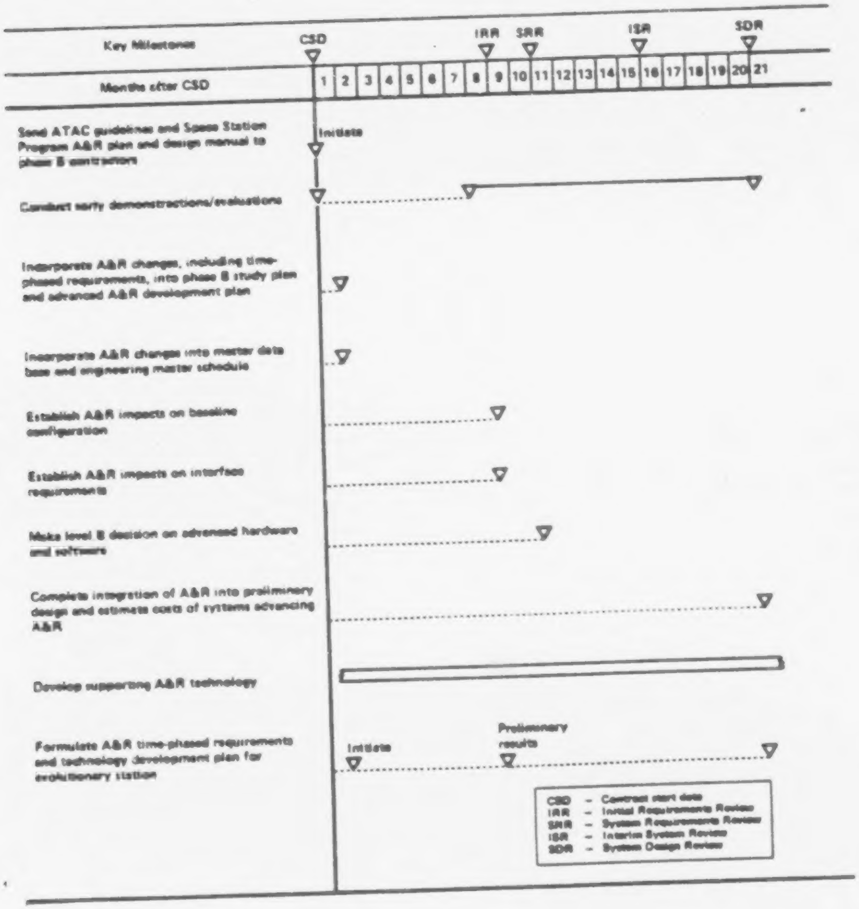
The Space Station Program Office at NASA Lyndon B. Johnson Space Center published the "Automation and Robotics Implementation Plan for the Space Station Program Definition and Preliminary Design Phase (Phase B)" on June 14, 1985, and distributed it to the space station Phase B contractors. This plan acknowledges the intent of Congress to create "a new generation of machine intelligence and robotics technologies."

Phase B A&R activities and milestones as they were proposed by the ATAC are summarized in figure 3-1.

The A&R Implementation Plan carefully outlines the actual process for Phase B, and groups the activities into three periods:

Contract Start Date (CSD) to Initial Requirements Review (IRR)

Figure 3-1 ATAC Proposed Phase B A&R Activities & Milestones



- Assess the degree to which A&R can be accommodated and implemented at IOC, and the rate at which advanced A&R can be accommodated during growth;
- Establish options for:
  - implementation of A&R at IOC; and
  - provision of scars and hooks to accommodate future incorporation of advanced technologies during growth;
- Conduct an Advanced Development program leading to design and planning of technology demonstrations for IOC and growth technologies;
- Develop industry technology transfer plan; and
- Update Phase B implementation plan.

IRR to System Requirements Review (SRR)

- Define preliminary requirements for A&R advanced development hardware, and requirements for software development, test, and evaluation leading to IOC A&R capability;
- Define selection criteria for the evaluation and incorporation of A&R into the preliminary design and define tools (e.g., life cycle cost models) to be used for the evaluation of designs against the criteria;
- Define Program-wide policies and guidelines for the detailed evaluation and implementation of A&R during the period SRR-System Design Review (SDR); and
- Define preliminary guidelines for design of satellites, payloads, etc., to be serviced/operated by A&R.

SRR-System Design Review (SDR)

- Evaluate candidate A&R elements for integration into the preliminary design
- Conduct test and demonstration activities according to requirements developed in the CSD-IRR period, as appropriate.

Phase B A&R activities are to culminate in eight products:

1. Preliminary designs for IOC A&R
2. Time-phased requirements for implementing A&R
3. Initial development and life-cycle cost estimates
4. Recommended growth strategy for A&R, including detailed requirements for scars and hooks
5. Requirements for payload and satellite design to be compatible with A&R servicing operations
6. An Advanced Development Plan for A&R
7. A Technology Transfer Plan
8. A&R demonstrations and evaluations to be conducted.

The Phase B Systems Engineering and Integration (SE&I) organization is to define the policies and guidelines for implementing:

- IOC A&R,
- Scars and hooks, and
- Advanced development.

The implementation plan recommends using "existing management structures as far as possible, augmenting them as necessary to address A&R."

PROGRAM NEEDS VS. RESEARCH NEEDS

As the A&R Implementation Plan makes clear, the space station program is planning to conduct no research with a view to advancing the state of the art in automation and robotics. The plan does not discuss research or technology development activities -- it confines itself to assessments, evaluations of options, development of policies and guidelines, etc. Even the "Advanced Development" program leads only to "design and planning of technology demonstrations."

Among the important issues not addressed in the Plan are the following: what organization is responsible for conducting advanced research in A&R for the space station program? Where are the resources to support such research expected to come from? Who has responsibility to see that results of A&R research are moved smartly into the mainstream program? Who has responsibility to ensure that the Phase B contractors incorporate advanced technology and strive to push it further? What is disturbing is not so much that these questions are not addressed in the Implementation Plan as that they are not addressed anywhere else either. However effective a programmatic tool the Plan may be, it appears not to be part of an overall NASA strategy to "a new generation of machine intelligence and robotics technologies." Indeed, this phrase, if anything, may divert attention away from important work that could begin now to promises of revolutionary advances tucked safely into the indefinite future.

There are at least two important reasons why NASA is not planning to conduct A&R research with funds from the space station program. The first is the language of PL 98-371 itself. The law requires that the ATAC report

> "identify... specific space station systems which advance automation and robotics technologies, not in use in existing spacecraft,"

and specifies

> "that the development of such systems shall be estimated to cost no less than 10 per centum of the total space station costs."

Perhaps the most significant point to be made about this text lies in what it does not say. In particular, it does not define "systems which advance automation and robotics," except to specify that they not be "in use in existing spacecraft." This specification does little or nothing to ensure that the state of the art in A&R shall be advanced because most, if not all, A&R technology in use in existing spacecraft is well behind the state of the art. The space station program, therefore, is certainly within the letter of the law in confining its A&R work to moving some A&R systems "not in use in existing spacecraft" from breadboard to operational systems.

Contrast this, however, with the language from Report 98-506, which provides a glimpse of what the Senate Appropriations Committee had in mind in sponsoring the legislation that became PL 98-371. Among other things, Report 98-506 states that

> "The Committee also expects the [space station] contractors to devote a significant portion of their effort pursuing the study of automation and robotics identified in the [ATAC] report with the objective of advancing the state of the art in these technologies and increasing their terrestrial application." [Emphasis added.]

At a minimum, the Report language seems to indicate that the Senate Appropriations Committee would have been pleased to see NASA go beyond the strict letter of PL 98-371.

In addition, PL 98-371 does not say that such systems shall be developed at a cost of no less than 10 per centum of the total space station costs. Again, a comparison with the language of Report 98-506 is in point.

> "The Committee believes that NASA needs to pursue the areas of automation and robotics more vigorously. Consequently, the bill language is intended to assure that such advanced technologies are indeed made an integral part of the planning and

development for a manned space station." [Emphasis Added]

In any case, the law required only the study of advanced A&R technologies whose development would cost said 10 per centum. Thus, the first reason that the space station program has not allocated any funds to advancing the state of the art in A&R is that the law does not require that this be done.

The second, and perhaps more important, reason why NASA is not planning to conduct A&R research with funds from the space station program is that the Congressional mandate requiring substantial NASA attention to A&R came well after initial planning for the space station had begun. By the beginning of Phase B many important performance specifications had already been set. These specifications, in turn, became significant cost drivers. Development costs for meeting these specifications were already pushing near the $8 billion total program envelope even before "advanced A&R" initiatives had been seriously considered.

Space station program managers have the goals, first, of making sure that what flies will operate successfully and, second, of flying as much good hardware as possible -- and of accomplishing both of these goals within budget. There is a natural divergence between technology developers, who wish to push new technology into operation as quickly as possible, and program managers, who wish to minimize technological risks in the interest of achieving an operational success. For a large, costly initiative like space station, this divergence is more pronounced.

Advanced A&R initiatives, therefore, are at a double disadvantage with respect to inclusion in the space station program. They have to be fitted around preexisting program commitments to other performance objectives, and, because they are "advanced," they are by definition technologically risky, i.e., operationally unproved.

On the other hand, there are some potentially useful A&R activities taking place at all the NASA Centers. A number of systems could, with appropriate encouragement from space station management, be moved from laboratory demonstration to flight hardware for inclusion in the IOC station. For instance, the Johnson Space Center has initiated a program of applied research addressing the application of expert systems to the space station and mission support activities. This Center-funded program is probably the second largest A&R program within NASA. The NASA Ames Center has the strongest claim to supporting basic research in A&R.

Furthermore, there are at least a few critical space station requirements that cannot be met except by the development of truly advanced A&R techniques.* One critical case is software verification. The number of lines of programming code required for operation of the IOC station will be some 10 to 20 times that used by the Shuttle. If the cost per line of code for the space station were the same as it was for the Shuttle, the total cost of software verification for the station would be prohibitive. Therefore, the means of software verification -- which, for the Shuttle, was essentially manual -- must be at least partially automated. To accomplish this task will require a real advance in the state of the art. Indeed, software may be the pacing item, both for space station and for automation and robotics.

Another critical requirement is to develop more dextrous manipulators. Although the current Shuttle Remote Manipulator System (RMS) used in connection with astronaut extra-vehicular activity (EVA) is almost certainly sufficient to assemble the space station, whether such assembly can be done safely with these capabilities is still an open question. It may well be that space station assembly can be accomplished more efficiently and more safely with a mixture of astronaut EVA and teleoperation, robotics, and automation technology well in advance of the RMS system. In any case, future satellite servicing planned to be accomplished with a station-based Orbital Maneuvering Vehicle (OMV) cannot be done without development of much improved dextrous manipulators. Here again, a real advance in the state of the art is needed.

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* Subsystem automation (for maintaining normal operations) and fault detection/identification are certainly feasible IOC applications of advanced AI techniques that could help prevent NASA's mission control costs from becoming prohibitive over the space station's life span.

Given these considerations, it seems necessary to conclude that a successful space station program cannot continue without substantial attention to advancing the state of the art in at least some A&R technologies. Furthermore, both the ARP and the ATAC reports have made it completely clear that **the space station program will not have been a success if it gives birth to an IOC space station that, even if nominally operational, cannot evolve gracefully toward ever more autonomous — and therefore, ever more fully automated — states. According to OTA workshop participants, such an evolution is highly improbable without explicit, immediate NASA management attention to the problem of establishing a substantial agency A&R research program in support of the space station.**

Current NASA policy, however, seems to be almost exclusively focused on producing an operational IOC station. NASA underscores this policy by dividing A&R technologies into three categories. First are those A&R applications that will be crucial to IOC station operation. These will be included in the annual budget requests within the overall $8 billion envelope.* In the second category are those applications that would materially enhance the productivity of the IOC station, but would not be necessary to its operation. Some A&R developments in this second category might be included in annual budget requests, depending on budgetary pressures in other parts of the program. The third category is comprised of those A&R applications that would require basic advances in the state of the art, could play an important role beyond IOC, and would be likely to have an important impact on terrestrial industries. In NASA's current planning, all of the applications in the third category and most of those in the second would be undertaken only if the Congress appropriates additional funding outside the $8 billion envelope for the IOC station. Participants in OTA's workshop fear that this division of A&R technologies may militate against significant agency support for fundamental research to advance the state of the art in A&R.

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* NASA has placed a certain amount of reliance on Phase B contractors to support automation and robotics. However, any development that the Phase B contractors are likely to fund will be oriented toward IOC. This work is vastly different from the advanced technology development that must be done prior to IOC in order to include appropriate hooks and scars to insure graceful evolution.

CHAPTER 4

THE NATIONAL RESOURCE BASE FOR AUTOMATION AND ROBOTICS

The U.S. civilian space program has been a source of inspiration to the nation for the past quarter century. In recent years, the high-technology area of A&R has not only captured public attention, but has also been considered by national leaders as key to a secure and prosperous future. Public Law 371 records the formal agreement of the President and the Congress that the NASA space station program provides a high-visibility opportunity to advance the state of the art in A&R. If satisfactory funding and management arrangements can be made within NASA in order to realize this opportunity, the result would almost certainly be a strengthened national resource base in advanced A&R as well as a far more capable space station.

However, it is also important to determine the current status of the resource base that could be drawn upon to support the beginning of a future NASA A&R initiative. For example, one problem NASA will encounter in constructing such a program is the limited size of the national personnel pool of researchers in automation and robotics. Qualified researchers, system designers, and developers are in great demand. Government agencies are competing against each other for the time and intellectual talents of these people. With the major emphasis within DOD, particularly DARPA and the Strategic Defense Initiative (SDI) program, on advanced automation, NASA will experience difficulty accessing this expertise unless a very significant, and visible, exciting program is constructed. Many researchers would prefer to work on a NASA advanced A&R program than on a corresponding program within DOD, but are not likely to have the option under present circumstances. Complicating this problem is the recent erosion of the fundamental research base as high-demand personnel leave universities and research laboratories.

This section of the paper presents a brief assessment of the availability and applicability of national resources and expertise in critical areas to space automation and robotics.

RESOURCE BASE FOR KNOWLEDGE-BASED SYSTEMS

Knowledge-based systems, of which expert systems are an example, have received a great deal of publicity recently. Much of this publicity, unfortunately, has bordered on hype, creating an environment of great expectations and probable underestimation of required investment. Many large corporations have created groups to solve some internal problems using expert systems and to sell these solutions to their clientele.

Given the planned evolutionary character of the space station, the characteristics of knowledge-based systems that make them particularly attractive for inclusion in the program are their inherent flexibility and their capability to handle complex decision tasks. Their knowledge bases can be updated as conditions change. The other side of this coin is that it may be more difficult to validate such systems.* Space-qualified software undergoes rigorous verification and validation before being committed to operational use. To date, there are no examples of spaced-qualified knowledge-based systems. This does not mean that expert systems should not be designed and built for use in the space station. It does suggest that one should be aware that new territory is being explored and that quick, inexpensive solutions cannot be expected.

The national resource base of competent researchers and innovative developers of knowledge-based systems is small. The problems associated with space use of knowledge-based systems may overwhelm the available national resources. DOD has been largely responsible for sponsoring the development of knowledge-based systems technology, and continues to support most of the national resource. A successful NASA program in this area may need to be a cooperative one with the DOD.

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* As noted earlier, software validation of knowledge-based systems cannot be done in the ordinary way because the algorithms of these systems are not deterministic.

Most knowledge-based systems are highly artful constructions, carefully crafted with heuristic techniques. Rigor must be developed and applied to the development of these systems if they are ever to be widely accepted for use in space. This could be a major NASA contribution to the national technology base.

RESOURCE BASE FOR TELEOPERATION & ROBOTICS

Teleoperation has been primarily the interest of the nuclear industry for handling radioactive materials and of the Navy and the private sector for undersea applications.* NASA has conducted related activities in its remote operation of lunar and Martian landers and free-flying scientific spacecraft, and more recently in its use of the Remote Manipulator System (RMS) on-board the Shuttle. The national technology base supporting teleoperation is not large, but it is probably adequate, at least for supporting the IOC station. Most of the capability resides in a few research laboratories and corporations, and these remain competent and available to support space teleoperation activities.

Robotics has developed more in the industrial sector, with a focus on applications in manufacturing. Industrial robotics has evolved to fill a manufacturing niche where lot sizes are too great for manual production and too small to justify hard automation. These lot sizes are typically in the thousands to tens of thousands. Another key factor in determining where robotics is used in manufacturing is whether or not means have been found to exploit the unique capabilities of robots (or their controlling computers).

Few robot manufacturers or system developers have yet begun to consider the long-term needs or potential associated with their technology, primarily because current technology has outstripped applications. A great deal of work remains to be done on issues such as how a CAD/CAM data base might be used with an automated planner and a robot to assemble or service another device automatically.*

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* Commercial undersea teleoperation, driven largely by the requirements of the offshore oil industry, is at least as well developed as the Navy technology, to the extent that the open literature is an accurate gauge of relative progress.

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Few have considered the potential evolution of teleoperation to robotics. This application may be an area in which NASA's interests are either unique or ahead of others. On the other hand, it may be possible that NASA's approach is backwards or even obsolete. On this issue, there are honest differences of opinion. In any case, NASA's concentration on teleoperation complements DARPA's emphasis on autonomy. As a rule of thumb, it seems to make sense to assign human beings (going EVA when necessary) to do unique, non-repetitive, difficult operations on the space station (e.g., satellite servicing), and autonomous robots to do repetitive functions (perhaps including part of the actual station construction).

Several major robotics laboratories have been organized recently, largely in response to industrial and defense interests in manufacturing. These offer capabilities that should be available to NASA for space robotics. The unique problems and opportunities afforded by the space environment are being seriously investigated only by a very few. In the view of at least some researchers, NASA has not done enough to encourage them to work in space robotics.

The national resource base in teleoperation and robotics, while not large, should be adequate for NASA's purposes. It has the potential to expand to fill NASA's needs, although there are many potentially critical problems in space applications of robotics that do not have analogues on Earth. However, DARPA is considering a substantially larger emphasis on robotics than is presently the case. If DARPA does move in that direction, the resource base may prove inadequate for both agencies.

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* See the OTA report Computerized Manufacturing Automation (OTA-CIT-235), pp. 73, 76-77, 79.

RESOURCE BASE FOR HUMAN INTERFACE TECHNOLOGIES

The automation studies done for NASA consistently identified speech recognition, natural language processing, and speech synthesis as necessary interface technologies for the space station. Predictive displays and fused displays that superimpose computed displays on observed scenes were also identified as necessary.

DARPA's Strategic Computing Program is concentrating substantial resources on speech recognition and natural language processing. If DARPA achieves its goals in these areas, NASA can probably capitalize, at relatively little cost, on the technology thereby developed. Speech synthesis is being adequately addressed by industry, a circumstance suggesting that no significant technology investment should be required by NASA.

Predictive displays and fused displays, however, pose a different set of problems, however, which may be more nearly unique to NASA's environment. Predictive displays are needed to accommodate communication time delays in accessing remote systems. These displays, requiring highly capable simulation facilities that currently are beyond the state of the art, are unlikely to evolve without direct NASA support. The DOD also has an interest in fused displays, particularly to support aircraft flight crews. The national resource base should be adequate for these tasks, but the technology programs will have to be developed. There are many fascinating opportunities in this area for the research community, many of whom would like to work on NASA problems.

Zero-G effects on human interfaces, particularly teleoperated systems in which precise control of body movement is required, are largely unexplored. Novel simulation facilities may be required. Very little work is currently focused on this problem, but there is little reason to believe that the nation's resource base could not address it, given appropriate incentives.

RESOURCE BASE FOR AUTONOMOUS SYSTEMS

The nation's resource base in autonomous systems is very thin. This is a new technology area about which little is known. Fundamental work needs to be conducted to develop an underlying system architecture, or model, that is sufficiently rich to capture the spectrum of applications of interest. This is an area requiring long-term dedication of resources and the development of a resource base. Early views of the problem suggest that the core issues involve procedural planning, simulation, monitoring, information fusion, fault diagnosis, and knowledge representation. DARPA's Strategic Computing Program is beginning to build much of this base in support of its Autonomous Land Vehicle and other programs. NASA can probably apply much of the DARPA research to good advantage in the space station program.

RESOURCE BASE FOR HIGH PERFORMANCE COMPUTING

Virtually all of the initiatives addressed in the automation studies require high-performance on-board computing. Much of this requirement stems from the need for real-time knowledge-based systems and high-volume on-board data bases.

These requirements will impose stress on the national resource base. Space-borne computing typically lags ground-based capability by at least one generation because of the time required for space qualification and the long development times associated with space projects. Success of space station automation applications depends not only on developing high performance computers, but also on accelerating the deployment of these in space. The DOD Very High Speed Integrated Circuit (VHSIC) program in conjunction with DARPA's Strategic Computing Program addresses part of this problem, but NASA may well need to conduct a parallel, complementary program to meet its own needs.

CHAPTER 5

SPACE A&R TECHNOLOGIES BENEFITING U.S. INDUSTRY

The requirements and opportunities for advanced automation and robotics in the Space Station Program offer potential long-term rewards to the U.S. industrial base that some calculate to be far in excess of the cost of developing the technology and deploying it in the space station. To date, however, the market for robotics is not limited by technology, but by the ability of firms to learn how to make use of current capabilities.

Table 5-1 (Table 7 from the ATAC report) identifies applications that could benefit from specific A&R technologies developed for the space station.

KNOWLEDGE-BASED SYSTEMS — INDUSTRIAL BENEFIT

Several research areas in knowledge-based systems have been identified as particularly important to NASA and the space station. They also have important spin-off potential to U.S. industry. These research areas include procedural planning, fault diagnosis, cooperating expert systems, and knowledge representation.

Procedural planning addresses the development of operational plans for a complex, dynamic system in which interactions among subsystems and between the system and a time-varying environment must be accommodated. Fault diagnosis involves detecting system operational anomalies in real time, inferring possible causes, establishing most likely explanations, and possibly testing hypotheses against the real system. Industrial use of knowledge-based systems in these areas is currently negligible, and very little R&D is being conducted, since the near-term return on investment is small (long-term, fundamental research being required). Long-term benefits are expected to be substantial,

Table 5-1 Potential Technologies Developed for the Space Station and Their Application

Potential Technologies	Applications										
	Assembly	Maintenance & Repair	Product/ Process/ Structure Inspection	Plant/ Facility Security	Factory Control	Transporting & Handling Toxic Materials	Pruning, Picking, & Cultivating Agricultural Crops	Medical Surgery	Computer Communications	Go-fer for Disabled	Fire Fighting
Hybrid Robot/ Teleoperator	X	X	X	X		X	X	X		X	X
Adaptive Control	X	X	X	X		X	X	X		X	X
Off-Line Robot Programming Through CAD/CAM Technology	X	X	X								
Tactile Sensors (Arrays, Force Feedback)	X	X	X	X			X	X		X	
Advanced Machine Vision (3D-Scene Analysis)	X	X	X	X			X			X	X
Mobile Robot Guidance/Navigation		X		X		X	X			X	X
Advanced Planning for Robotics	X	X	X	X		X	X			X	X
Dual Arm Robotics	X	X				X				X	X
Dextrous Manipulator	X	X	X				X	X		X	
Robot Application Modeling by Visual Simulation	X	X				X	X	X			X
Diagnostic Expert System		X	X	X	X						X
Distributed Computing		X			X				X		
Advanced Data Storage Technology		X	X	X	X				X		
Intelligent Man/ Machine Interfaces	X	X	X	X		X		X		X	X
Intelligent Remote Sensor Technology		X	X	X	X						X
Energy Management/ Advanced Process Control Technology					X						
Advanced Fault-Tolerant Disciplines		X			X				X		

however.

The space station is largely a closed environment consisting of multiple subsystems that must cooperatively interact. Expert systems are envisioned to control many of these subsystems. Therefore, the controlling expert systems must also interact in a cooperative fashion. The problem of cooperatively interacting subsystems is common to most large systems. Over the long term, therefore, NASA advances in cooperating expert systems may yield substantial industrial spin-off. As noted before, DARPA is also doing a great deal of research on these systems.

Each of the automation studies identified the need for effective means of representing knowledge for use by space station systems. In order to increase the autonomy of the space station, one would like a complete set of information locally available to the space station, from initial design characteristics, through maintenance and repair records. Additionally, one would like the space station to have rapid access to information about its immediate environment and its users. The organization of this information in such a way that it can be used by knowledge-based systems is called knowledge representation. Fundamental problems remain to be solved in knowledge representation for complex real-time systems, but their solution will be highly valuable to other large-scale systems.

Major early beneficiaries of advances in knowledge-based systems technology for the space station include large-scale design, engineering, and production industries such as aircraft, ships, automotive, and electronics. The development of knowledge-based aids to the crew of the space station may also spin-off into aids to operators of other large-scale systems (e.g., nuclear power plants), into consumer-oriented services for instruction and entertainment, and into aids to decisionmakers in a variety of technical areas.

TELEOPERATION & ROBOTICS — INDUSTRIAL BENEFIT

The development of teleoperation and robotics technologies for space can have a major impact on ground-based uses of manipulator technology. Table 2-8 suggested some of these applications. The space station offers the opportunity to advance this technology in directions that it might not otherwise go, and certainly provides incentive to accelerate the entire development process.

General Electric's proposal for an automated, space-based manufacturing facility employing robots is intriguing in its own right; its development could also substantially advance the ground-based technology for automated, flexible manufacturing. The space environment would force GE to address automating processes such as scheduling, servicing, maintenance, and repair that might otherwise be treated manually in a ground-based facility. The solutions to these problems and experience gained in applying them to in-space manufacturing could be transferable to other manufacturing processes.

Satellite servicing is NASA's dominant interest for space teleoperation and robotics. This is the application that led to the concept of evolving from teleoperation to robotics. Satellite servicing presents major technological challenges that might result in important spin-offs to ground-based applications. These include light-weight, high-precision, dexterous manipulators; multiple-arm coordination; sensor-based intelligent control; and automated planning derived from CAD/CAM data sources.

Some industrial manufacturers have only begun to address the complex problem of deriving an operational control sequence for a robot from CAD/CAM data and high-level commands, but this is precisely the long-term goal of space-based satellite servicers. If NASA can solve this problem for servicing satellites, a major step forward will have been taken that will have a direct effect on labor-intensive industrial robot programming. This technology is also clearly applicable to other servicing applications in hazardous environments such as nuclear facilities, undersea, and in mines.

HUMAN INTERFACE — INDUSTRIAL BENEFIT

The argument was made in section 4.3 that NASA's role in speech recognition, natural language processing, and speech synthesis need not be extensive. The space station does offer the opportunity for NASA to contribute significantly in other human interface areas, however.

Space station automation studies identified the need for predictive displays and displays that fuse information from multiple sources. These displays are needed primarily to accommodate time delays for operations requiring real-time interaction with the operator and to superimpose nominal information on observed information. The resulting display, simulation, and data management technology would be transferable to commercial uses in system monitoring, training, maintenance, and exploratory scenario development.

The space station will be sufficiently complex that no crew member will be able to understand its complete operation. Whereas complex systems (including the Shuttle) typically rely on paper media to document their design and operation, the space station will need a much more effective and efficient way of providing this information to the crew. Automated systems will have to be designed to be capable of giving an account of their activities, thus presenting a relatively standard, non-threatening user interface. These requirements present challenges in system documentation and interface design which have barely begun to be addressed, but which are critical to the effective and efficient operation of the space station. Advances made in this area will be directly and broadly applicable to ground-based industries. This may be a high leverage area which, to date, has received little attention because the costs associated with doing it poorly, while great, are neither immediately apparent nor well understood.

AUTONOMOUS SYSTEMS -- INDUSTRIAL BENEFIT

The current interest in autonomous systems is largely limited to defense applications and space applications. Essentially, the research is aimed at deriving robust control, over extended periods of time, of large-scale, highly complex systems that do not lend themselves to automated control using classical techniques. DARPA's program to develop an Autonomous Land Vehicle (ALV) is one good example. When the program is successfully completed, the ALV will be able to navigate through off-road terrain at moderate speeds, relying primarily on a digital terrain database and dead reckoning. It will rely on computer vision to update its Land Navigation System, to identify obstacles to be avoided, and to follow roads when available. The long-term potential for applicability to non-defense, earth-bound applications is significant, but largely unexplored.

Potential near-term commercial applications of autonomous systems include systems which currently require human monitoring and control, but which have relatively high occurrences of operator error because of boredom or inability to interpret the system state rapidly while under stress. Longer-term applications could include fully automated manufacturing systems appropriate for handling piece parts, small lots, or large production runs, depending on product specifications and orders. The integration of autonomous systems technology with robotics technology could provide the foundation for a new generation of intelligent robots to address some of the applications listed in table 2-8.

Commercial interest in autonomous systems is expected to increase as DOD and NASA display some successful demonstrations and applications. This is considered an area of high-potential, high-technological risk, and long-term application.

HIGH-PERFORMANCE COMPUTING -- INDUSTRIAL BENEFIT

The space station A&R studies all concur that on-board computing requirements exceed commercially available space-rated processors. NASA's needs coupled with those of DOD and other technology-oriented agencies will ensure a continued need for government-sponsored computing research and technology.* Experience suggests that advances fostered by this research will be quickly absorbed by private industry.

Specific areas in which space station A&R needs may drive technology include computer networking, high-level language standardization, special-purpose languages (e.g., for robot programming), real-time systems, CAD/CAM standards and interfaces, fault tolerance, parallel processing, symbolic processing, space-rated terabyte storage, and large-scale data bases. Technology developed in each of these areas is immediately transferable to commercial application.

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* See the OTA report Computerized Manufacturing Automation (OTA-CIT-235), p. 373.

APPENDIX A

OTA TESTIMONY
BEFORE THE SUBCOMMITTEE ON HUD - INDEPENDENT AGENCIES,
COMMITTEE ON APPROPRIATIONS,
U.S. SENATE,
29 March 1984,

ON
THE USE OF AUTOMATION AND ROBOTICS IN THE SPACE STATION PROGRAM

Any program to place substantial, essentially permanent infrastructure in orbit around the Earth will be a major, long-term undertaking. The importance of any "space station" will continue to be felt well into the 21st century -- beginning with the next 10 to 15 years of its development and construction, and extending throughout the subsequent 20 to 30 years of its full operational use. Thus, the President's proposal that NASA be charged with developing a "space station" prompts the Congress to think and decide relatively quickly about a program many of whose more important pay-offs may not become evident for perhaps 20 years. As OTA has pointed out in recent testimony, any such program should be undertaken with appropriate, long-term ends in view.

Although civilian space operations are too costly to be justified solely as a means for advancing the field of automation, they may nevertheless be undertaken in such a way that progress in automation is a concomitant of increasing our prowess in space capabilities more generally. Indeed, the "space station" program would provide perhaps a unique opportunity in which sufficient personnel and resources would be concentrated to provide a critical mass that could substantially advance the state of the art in automation. But what are the realistic prospects for the study and exploitation of automation in space?

The workshop participants, all of whom have either expertise in one or more aspects of automation, substantial experience in working with space systems, or both, arrived at a general consensus of cautious optimism. This consensus may be summarized in the following five points.

1. Our present space activities simply would not be possible without automation. In order to monitor and remotely command and control many important in-space assets and activities, people on the Earth's surface or on the Shuttle rely on systems that are at least partially automated.

2. More advanced automation has considerable potential to allow additional space tasks to be accomplished, but it cannot play a key role in any "space station" program of the 1990s unless its level of support is greatly increased and its uses clearly identified and broadly articulated. Research in the various fields of advanced automation -- robotics, teleoperation, expert systems, and artificial intelligence -- is moving forward, but it has not been given the national emphasis required to make it a significant contributor to space activities in the next decade. Researchers working on advanced tasks number only a few hundred, and the magnitude of NASA support for advanced R&D in this area falls into the range of $100,000-$200,000 per contract.

3. Interactive combinations of people and automated systems will expand indefinitely into the future, with automated systems becoming capable of more and more sophisticated tasks as time goes by.

4. Development of the capabilities to accomplish increasingly complex in-space tasks by means of advanced automation will benefit the entire range of automation disciplines. It is one area of space technology development that undoubtedly has spin-off potential for Earth applications.

5. The development of machine systems incorporating perception, motor skills, and artificial intelligence comparable to those of human beings requires so many breakthroughs that one cannot rationally predict when, or if, they will be available. However, many of the tasks envisioned for any "space station" could be performed at lower levels of automated capabilities, especially if human beings are remotely present.

From these points of consensus, it seems clear that both advanced automation and future space operations would be benefited by more closely coupling them in any "space station" program. Thus, it does seem to make sense to use any "space station" program to drive R&D in automation, provided that objectives are carefully chosen and expectations for success are not placed unreasonably high.

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Three major issues emerged at the workshop: how best to push toward more capable automated space systems and the wider use thereof; how to determine the optimum division of responsibility between people and machines; and how to estimate the importance of space automation to Earth applications.

1. Toward Automated Space Facilities

Provided that the environment is highly predictable and the activities are sufficiently circumscribed, there already are real opportunities for introducing useful automated equipment to accomplish some tasks and to do so relatively inexpensively. (One possibility would be to access, by remote operation, an infrared telescope in a satellite and recharge it with liquid helium.) But, being able to cope with an unconstrained environment and a wide range of activities is well beyond the capabilities of currently foreseeable machines.

Automation, of course, is a dynamic field, and capabilities will increase over time. It is therefore important that the original architecture of any "space station" not preclude the addition of automated systems as they become available. (This procedure was not followed on the Shuttle.) Especially since the technology is essentially "frozen" well before the actual hardware is flown, an incremental approach to the acquisition of space infrastructure might, with respect to the issue of incorporating automated systems, be preferable to acquiring an essentially complete operating capability all at one go.

Automating much of the ground support of any "space station" could be begun now. Other functions automatable in the near term are rendezvous and docking (tasks which the Soviets have accomplished in an automated mode for more than a decade) as well as scheduled maintenance and monitoring.

At this stage of the development of automated systems, it is important to pick some long-term goals well in advance of the state of the art, and to measure progress en route to that goal with a number of frequent "real-world" R&D milestones. One possible generic goal would be the demonstration of a robotic device capable of assessing an incompletely known situation, drawing upon its own knowledge base, communicating back to a human being on Earth or at another location in space for some advice, and, upon receipt of that advice, automatically implementing a complex repair or assembly task. Specific R&D milestones for this generic goal would include the development of dextrous hands, flexible manipulators, and reliable three-dimension vision systems. It would be NASA's task to choose such goals and milestones as would be useful both for future space systems and for ground applications.

2. People and Machines

The U.S. civilian space program has a history that is relevant to the development of long-term in-orbit infrastructure. In particular, there is a strong emphasis on manned space flight, and the expectation that people will be in space on the Shuttle for the foreseeable future. Given that reality, it makes sense to make the best use of human capabilities supported by automation.

Also, the maximum possible level of automation may not be the optimal level. Human beings have been found to be far more productive workers in space than had been generally expected.

On the other hand, there may be a tendency to rely too much on the human presence in order to avoid having to face and solve difficult technological problems.

In any case, this is not an either/or situation: innovative syntheses of the capabilities of highly trained people and sophisticated machines could be the rule for the predictable future. With the existence of high-quality sensors, manipulators, and communications, the human operator on the ground or in space could remotely perform many of the required space functions, flexibly and adaptably. Further, through supervisory control, the human could communicate sub-tasks and conditional information to a robotic device which could implement those sub-tasks and quickly report back to the human when it had completed its task -- or ran into unforeseen difficulty. In other words, the machine could ask for help whenever necessary. Thus the speed, power, and precision of automation could be combined with the pattern recognition and judgmental qualities of the human being without paying the large cost of actual human presence. The appropriate mix of human and automated capabilities has to be determined on a case-by-case basis.

3. Importance to Earth Applications

NASA is a national resource, a technology driver for the whole nation. International competition in automation technologies is a serious threat to U.S. commercial-industrial leadership. The "space station" program would be a good opportunity to help move our R&D efforts in automation onto a faster track. It has the additional advantage that there are no overriding institutional constraints, e.g., that workers would be concerned about the loss of their jobs as a direct consequence of the effort, or that certain important technology demonstrations would be too costly in the context of terrestrial practice.

Currently much of the research in artificial intelligence is being focussed on near-term applications; similarly, the development of robotics is tightly constrained by the current requirements of Earth applications. The "space station" program could provide an R&D incentive to work on research topics that are at once truly advanced and germane to the "real world." Possible R&D objectives could include a free-flying robot operating under supervisory control to service satellites, or an automated system to undertake hazardous tasks such as handling cryogenic fuels.

If automation R&D were seriously undertaken in connection with a "space station" program, the many tasks needed to operate the system could be analyzed to select several generic problems of clear relevance to Earth applications. These could include the development of dextrous fingers and hands, flexible manipulators, and advanced sensors, and, especially, the integration of real-time sensing data into the knowledge base of expert systems. In addition, new parallel hardware would be required to meet the weight and real-time constraints of space applications. All of these components are necessary to obtain truly flexible control in not wholly determined task environments such as are found in space (or in mining, ship-building, undersea work, construction, firefighting, and medicine), in contrast to those of the factory production line. Such a space program would present the opportunity to develop and demonstrate coordinated, integrated control over a wide variety of interacting systems.

Beyond these advantages would come the general development of more sophisticated knowledge and experiential bases in our scientific and engineering communities.

APPENDIX B

PROS AND CONS OF INTERNATIONAL INVOLVEMENT IN AUTOMATION AND ROBOTICS FOR THE SPACE STATION

Canada, Japan, and ESA are involved in Space Station Phase B studies. They, along with ESA member states could, to varying degrees, contribute A&R technology to the space station program.

International involvement in any large program like the space station introduces both opportunities and difficulties. The advantages of international involvement in space station A&R include:

- decreased direct costs to the United States;
- increased innovative scientific and commercial applications;
- decreased likelihood of direct, unproductive competition through related projects;
- wider productive competition, potentially increasing the quality, capability, and cost-effectiveness of the product;
- improved technology transfer to the United States, resulting in greater U.S. industrial efficiency and competitiveness;
- a clearer message that the space station is a project encouraging world peace through cooperation; and
- access to unique technology capabilities available only from international partners.

However, there are also strong impediments to effective involvement of international partners in space station A&R. These include:

- U.S. sensitivity to dissemination of technical information with potential military or economic value;
- explicit Congressional interest in advancing U.S. competitiveness;
- lack of international standards in areas critical to effective use of A&R (e.g., communication protocols and robot programming languages); and
- import/export controls.

In addition, there may be specific disadvantages to the United States if international partners contribute to the development of space station A&R. Most notably:

- the foreign developer may acquire a commercial advantage in products and technology;
- U.S. industry will not benefit from the experience of developing a new process or product from scratch;
- space station program management becomes more complex, inhibiting progress; and
- overall risk to the Space Station Program (political, economic, etc.) is increased.

In order for international partners to contribute A&R technology effectively to Phase B studies for the space station, NASA needs to determine both the levels of system modularity for the space station, and the levels at which foreign capabilities can be introduced. Presently, the United States is solely responsible for the space station design, though potential international participants do have input into the process.

Certain applications such as satellite servicing are viewed internationally as economically attractive capabilities to market. Future negotiations will likely have to clarify the relationship between the developer of space-based servicing equipment, for example, and the provider of those services. As the space station evolves, it will continue to foster debate, and possibly even litigation, regarding access to space-based resources and capabilities.

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Reference information for footnote on page 84 needs to be requested from Ron Larson.